Management Strategy for Smart Grid –

A Cluster System Analysis Method

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A thesis submitted in partial fulfillment of the

requirements of the

University of Bolton

for the degree of

Doctor of Philosophy

This research work was carried out

in collaboration with

The South Westphalia University of Applied Sciences

Division of Electrical Engineering

Soest, Germany

July 2014

Dedicated to

my family

my professors

my friends.

Abstract

Recently, Distributed Generation (DG) technologies become more potential in electricity supply contributors to electric utilities. It leads to increase the grid integration ratio of DG. Thus, the trend of decentralized power systems has been considered as a future of energy supply systems. According to this fact, the distribution systems must be changed from a passive control area to be an active control area. To overcome and realize this issue, the clustering power systems approach is developed. The main idea of this concept is to coexist the DG with the conventional power systems. Therefore, the system structure and the control approach are introduced and developed based on the conventional system. The cluster network structure keeps the main idea of conventional interconnected grid. Consequently, the clustering power systems concept intends to cluster the power systems into several areas, called cluster area. As a direct result, the cluster network structure can be described like the interconnected grids.

In order to empower and turn the ordinary passive distribution system to be the active system, the clustering approach announces the distribution management system (DMS) for the cluster automation application. The DMS application is the cluster controller and management, which applies in each cluster area. To accomplish the DMS functionality, control functions based on cluster concept have been developed continuously, e.g. the multi-level clusters control approach. Besides the development of cluster control approach, a cluster analysis strategy is cautiously considered as well, since it is a key to complete a cluster management and an optimization process. A hybrid calculation technique is consequently proposed to be a solution for cluster analysis, because it offers a possibility to integrate a character of interconnected clusters into the analysis. Hence, the cluster analysis can be employed in a decoupling way. To evolve the cluster analysis, a character of distribution network has to be taken into account. The character of distribution network is dominated by the unbalanced condition e.g. multi-phase feeder system. Moreover, the penetration of DG units can cause unbalanced condition as well, e.g. single phase feed in of home PV systems. To deal with unbalanced condition, an asymmetrical sequence hybrid and asymmetrical three-phase four-wire hybrid analysis method is rolled out, both are developed based on a difference issue of load flow studies.

All in all, the cluster analysis is a key to execute optimization and management process of cluster system operation as well as the supervisory of automated cluster control application. Finally, the proposed hybrid analysis is ready to be the main function in order to ensure and forwards the development of clustering power systems philosophy to be one of the best solutions for the future smart gird applications.

Acknowledgements

This research study was carried out through the department of Power Systems and Power Economics of the University of Applied Science South Westphalia, Soest, (Germany), in partial fulfillment of the requirements of the University of Bolton (UK) for the Doctor of Philosophy degree from January 2010 until December 2013. The research was financially supported by the Federal Ministry of Education and Research in Germany.

I would like to acknowledge my supervisor, Prof. Dr.-Ing. Egon Ortjohann from the South Westphalia University of Applied Sciences, for his distinguished supervision and excellent guidance, which contributed the successful research study.

I would like to thank my supervisor and director of the study, Prof. Dr. Danny Morton from the University of Bolton, for his great advice and support in the entire research period.

I would be remiss if I didn't acknowledge my colleagues in the Power Systems and Power Economics laboratory. I would like to particularly thank Mr. Andreas Schmelter (Dipl.-Ing), Mr. Manfred Wilczek (Dipl.-Ing.), and Mr. Carsten Mauer (Dipl.-Ing) for their great constructive discussions, cooperation, and technical support. My appreciations also go to Mr. Marius Hoppe (M.Sc.), Mr. Hakam Saffour (M.Sc.), and Mr. Sasiphong Leksawat (M.Sc.) for their unlimited assistance and time.

Many thanks also go to all postgraduate and undergraduate students who worked in the laboratory through this study period.

Last but not least, I would like to express my thanks to Dr. Chawanakorn Mantala, for his help, especially in difficult situations.

Declaration

“No portion of the work presented in this dissertation has been submitted in support of another award or qualification either at this institution or elsewhere.”

(Paramet Wirasanti)

Keywords:

Active Distribution Network

Smart Grids

Clustering Power Systems Philosophy

Multi-Level Cluster Control Application

Hybrid Calculation Technique

Asymmetrical Three-Phase Load Flow Calculation

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List of Abbreviations

Abbreviations	*Description*
AC	Alternating Current
AD	Active Demand
ADN	Active Distribution Network
ANM	Active Network Management
AVR	Automatic Voltage Regulator
BEMI	Bidirectional Energy Management Interface
BPL	Broadband Powerline
CIM	Common Information Model
DC	Direct Current
DERs	Distributed Energy Resources
DG	Distributed Generation
DGC	Digital Grid Controller
DMS	Distribution Management System
DSO	Distribution Systems Operator
ECS	Energy Conversion System
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
GF	Grid Forming
GP	Grid Parallel
GS	Grid Supporting
HMI	Human Machine Interface
HV	High Voltage
ICT	Information and Communication Technology
IED	Intelligent Electronic Device
LV	Low Voltage

MV	Medium Voltage
NEV	Neutral to Earth Voltage
NIS	Network Information System
PC	Primary Control
PLC	Power Line Communication
PV	Photovoltaic
RESs	Renewable Energy Sources
RMS	Root Mean Square
SC	Secondary Control
SVC	Static VAR Compensator
TC	Tertiary Control
TSO	Transmission Systems Operator
UCTE	The Union for the Co-ordination of Transmission of Electricity
VPP	Virtual Power Plant
WEC	Wind Energy Converter

List of Variables

Variables	***Description***
$\underline{H}$	Hybrid matrix
$\underline{I}$	Complex Current
$\underline{S}$	Complex Apparent power
$\underline{T}$	Sequence Component to Phase Component Transform Matrix
$\underline{U}$	Complex Voltage
$\underline{X}$	Complex Value
$\underline{Y}$	Complex Admittance
$\underline{Z}$	Complex Impedance
P	Active Power
Q	Reactive Power
$0,1,2$	Lower suffix for Sequence Components
a,b,c,n	Lower suffix for Phase Components and Neutral
c	Lower suffix for Compensation element
d	Lower suffix for Decoupling element
k	Lower suffix for Known element
u	Lower suffix for Unknown element

1. Introduction

Global power systems are currently in the transition to move from conventional power generation to sustainable power generation based on renewable energy sources (RESs). An improvement of grid operation and reliability is subsequently taken into account in the term of "Smart Grid". Meeting the challenges of future electrical power systems enables a research and an innovation. Dealing with the changes in the power supply process e.g. technical, economic and regulation, are required a good lesson from historical cases. Thus, it is worth to mention that a background of existing power systems is important to keep in mind as a principle for future power systems. Hence, the thesis introduces an evolution of electrical power systems in order to point out a stepwise development direction including requirements of future power systems. This general discussion is a key to success next generation of electrical power systems.

1.1 Evolution of Electrical Power Systems

Presently, electrical power supply systems are facing significant change due to the high penetration of distributed generation (DG) in last twenty year [1], and [2]. Obviously, there are plenty of new aspects about future power process e.g. an active distribution network (ADN), a revision of power flow and a liberalization of electrical energy trade. To accomplish those expected characteristics, a decision must soon be made to close the gap between a bulk transmission network and a future network. However, the development track must be clarified that

"The future power system is an evolution not a revolution.(1)*"*

(1)This quote has been mentioned and emphasized through many international power systems conferences and articles. This section initiates with the introduction regarding the evolution of electrical power systems. The conventional power systems are firstly presented in order to remind and illustrate the background of existing systems, which are still dominant. The decentralized power system based on RESs is secondly mentioned; this approach has been lately considered as a sustainable system. Finally, the requirements and the driving forces of future electric power system are pointed out. This will describe the vision, the objective, and the clear steps for the development in order to reach the successful future power supply systems.

1.1.1 Conventional Power Systems

Traditionally, the conventional power supply systems can be mainly defined by large centralized power plants, transmission lines, transformers and loads. This results in a clear structure of electrical systems, which is described by transmission network and distribution network. The main component on transmission network is generation units e.g. coal, hydro and nuclear power plants. From generation units, the power is injected into transmission systems in order to deliver to consumption units. This transmission level is operated under the high voltage level (110 kV) or extra high voltage (200/380kV). The delivered power enters into distribution network through substations. Based on traditional systems, the substation is a passive power exchange unit. It is used for controlling and transferring the power to consumption units, which can be everything from a big industry plant to small equipment in a house, and they are normally located at medium voltage level (10/30kV) and low voltage level (0.4kV), respectively. An overview of conventional power systems is portrayed in Fig. 1.1. According to the system structure, it is obvious that the power flow process is delivered from centralized power plants down to consumption units in distribution network. This character of conventional systems describes the power flow process as a unidirectional.

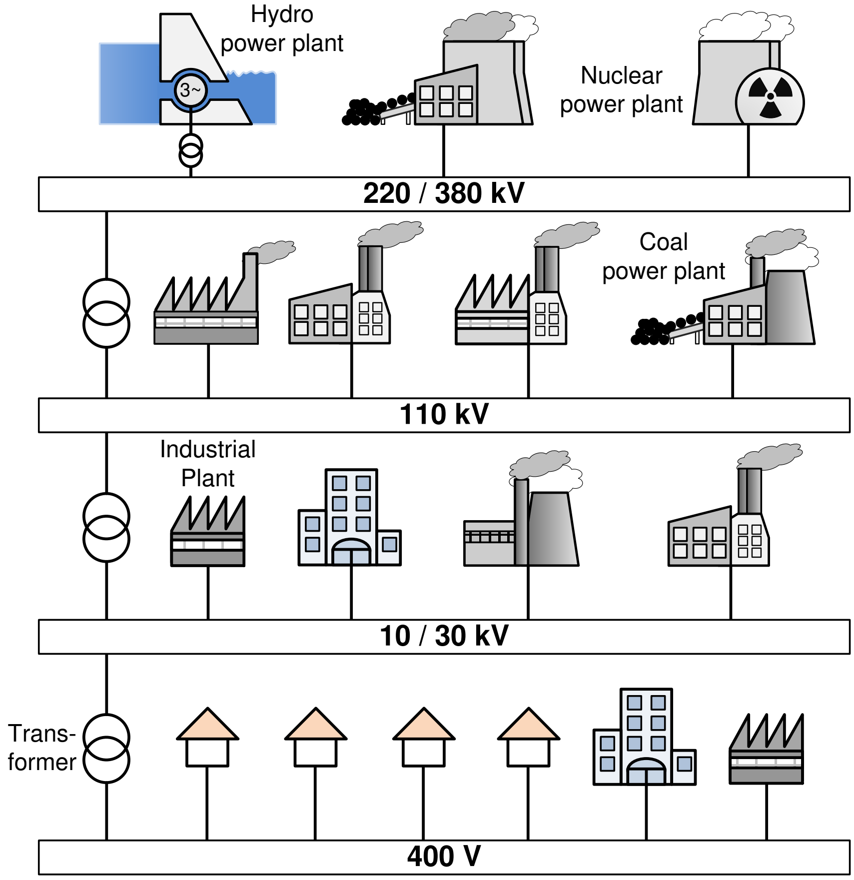


Fig. 1.1: Overview of conventional power systems

Regarding the unidirectional power flow process, it is obvious that the system operators and the system controls are functioned and managed as a centralized operation. This can be also referred to the controlling and stabilization of power systems state variables, frequency and voltage. Those variables are controlled and stabilized by central power plants on transmission network. According to those facts, the transmission network is named as an active control area. On the other hand, the distribution network can be implied as a passive area, because there are only consumption units on this area.

Having a look on the market system based on conventional power systems, commonly, the target of electric power system is to satisfy the customer demands in financial. Thus, the electricity markets come to take a part of electrical energy trading. The trading participants have the possibility to balance their purchase and sale obligations in order to provide low transaction costs and a neutral price for the wholesale power. It is obvious that the persons, who manage the market mechanism, are the electrical energy trader companies, capacity holders, and power generation companies. Hence, the current market system is similarly operated as centralized market system because the market participants are basically located on transmission level. The discussion on this section is aimed to illustrate the conventional system, which is still dominant. Further discussion of the conventional supply systems, the transmission code regulations and standard can be found in [3], [4], [5], [6], [7], and [8].

Nevertheless, the central power plants e.g. coal power plant and nuclear power plants are presently considered to be reduced or removed from the power systems, since they cause the global environment problems. For example, the recent 2011 Fukushima accident [9], this issue alerts the people around the world to realize the danger of nuclear power and refuse this kind of power. Moreover, the centralized power systems structure can cause the electricity black out. The major black out in the Midwest and Northeast United States and Ontario, Canada on 2003 may illustrate a good example. Around 50 million people stayed without electricity for 4 days. The event contributed to at least 11 deaths, and damage cost are estimated around 6 billion US dollar [10]. Due to those reasons, a trend of decentralized power systems based on RESs has been intensively taken into account as sustainable power systems. This is another chapter of the power systems evolution. The follow section is donated to illustrate and clarify the concept of decentralized system as well as the expected change based on technical and economical approaches.

1.1.2 Decentralized Power Systems

Presently, the efforts to mitigate climate change across the world are focusing on the expansion of renewable energy production. Thus, electrical power supply systems are recently facing significant change regarding the high penetration of DG based on RESs, especially in

European Union. Currently, Sweden has already reached 46.8% of renewable energy share in total electrical energy consumption, Latvia (33.1%), Finland (31.8%) and Austria (30.9%) [11]. Another country, which is worthy to point out, is Germany. The renewable energy share in total electricity consumption has been dramatically increased from 4.8% in 2004 to 23.6% in 2012 [12]. The most vivid growing systems are the photovoltaic systems and wind energy systems, which 90% and 95%of install capacity is located in distribution network [1], respectively. Those mentioned situations are an obvious evidence to show that the DG units based RESs has been considered as the sustainable power supply systems. Furthermore, the DG technologies become more potential contributors of electricity supplied to electric utilities. Thus, it can be foreseen that the grid integration ratio of DG will continuously increase. In order to figure out the characteristic of decentralized power systems, the system structure is firstly considered. An overview of decentralized power system is shown in Fig. 1.2.

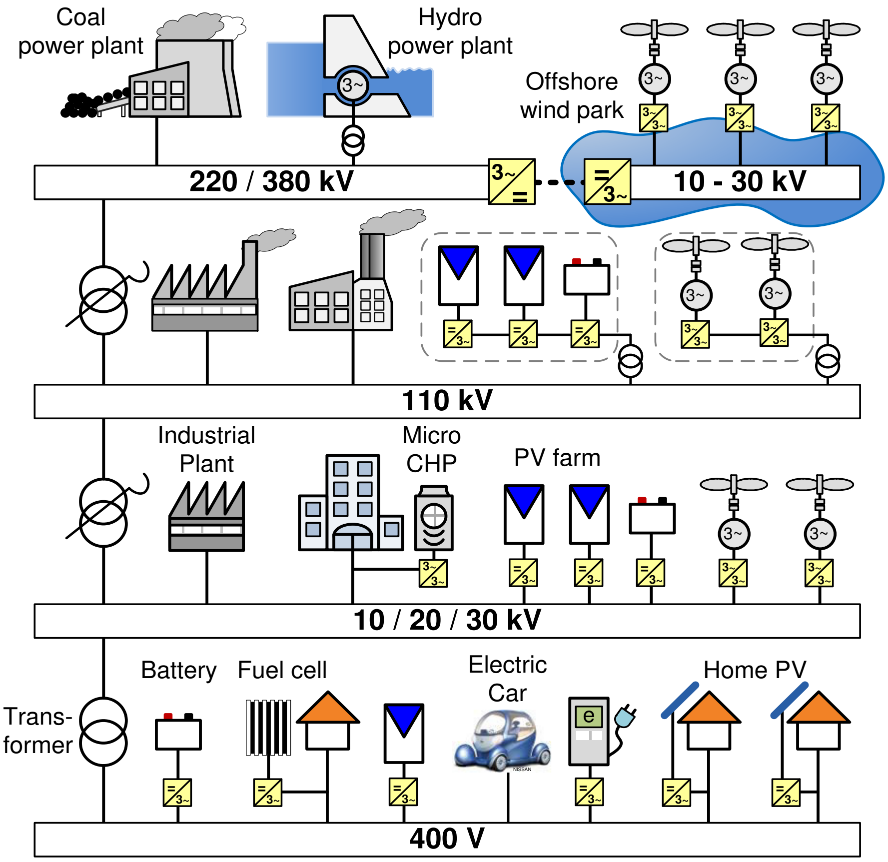


Fig. 1.2: Overview of decentralized power systems

It is noticeable that the network structures, power systems voltage levels are basically based on conventional power supply systems. The change is the penetration of DG units in the entire system. The key element for the penetrating of DG units is an inverter. The inverter is an interface unit, which provides opportunity to convert energy sources into the electrical network. Moreover, advance control functions can be implemented into inverter. Regards that fact the approach of ADN has been launch and widely discussed. In [13], the definition of AND is clarified. It can be briefly summarized that the passive character of distribution network will be changed to active character in an automated way. This means that the local consumption units can be turned to production units. This is a birth of *"Prosumer"* definition, [14].

Since the DG units have more potential in electrical energy producing and they are expected to participate in grid control application in order to establish the active character in the entire power systems. It can be predicted that the power flow process can be reversed from the distribution level to the transmission level. This means that the traditional unidirectional power flow will be changed to bidirectional process. However, this approach requires a rearrangement of technical control concept based on power systems state variable because it can cause power systems stability problems. Moreover, many electrical infrastructures are also needed to be replaced by a new component, which can support the bidirectional power flow process. Due to those reasons, this bidirectional approach is still under the development process.

Considering the view of electricity market system, it can be implied that the decentralized market system will be more competitive, since the electrical power generation is growing in decentralized systems. Consequently, a liberalization and privatization of electricity market has been presently discussed. Plenty of development models have been lately developed and introduced. Nevertheless, the implementation in a real system still needs more investigation.

Those mentioned changes in power systems, the penetrating of DG units based RESs and the liberalization of electricity, can ruin the reliability of convention power systems [15]. Thus, to move toward the decentralized power systems or future power systems, cautious study is required in order to provide a good strategy for the technical change and economical change. As mentioned that the future power systems is the evolution not revolution, therefore, the development outlines for the future power systems based on this statement are summarized in the next section. Further discussion of the decentralized power systems can be found in [16], [17], [18], [19], [20], and [21].

1.1.3 Key to Successful Future Power Systems

To realize the future power systems, it involves the ongoing studies and developments of technical issues and economic issues. Lately, a topic of *"Smart Grid"* is launched and has been discussed as a vision of future power systems. Unfortunately, there is no agreement or a general acceptance for the smart grid definition. However, the European Commission has delivered one of the good definitions that *"the smart grid is an electricity network, which can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both in order to efficiently deliver sustainable, economic and secure electricity supplies"* [22].

Regards that point of view, the intelligent infrastructures have to be integrated into network in order to establish the interaction between all units in network. Based on this issue, the term of *"Smart Market"* is also started to discuss, since the interaction between generation units and consumption units are active [23]. According to those mentioned issues of electricity grid, it is needed to state that those are recent concepts of this moment. Due to this point, the evolution of electricity grid can be also changed in another aspect in the future. Therefore, this thesis is going to point out and emphasize the key concept for sustainable development.

Before start the discussion for sustainable development strategy, it is noteworthy to state that the conventional power supply system still serves main consumptions of electricity demand with reliability. However, with a variety of problems e.g. its cost and sustainability, it challenges the approach of RESs in the long term system. The RESs can be considered as small generation units, which are penetrating in distribution network. On the other hand, the RESs can be also considered as huge power plant in transmission network e.g. offshore wind park. Thus, it is impossible to cut the conventional process. Furthermore, this must be taken into account as the first priority. Consequently, this thesis emphasizes that any novel development must be coexisted with conventional systems. The technical issues, especially power systems state variables control, have to be cautiously studied, since the current manner of distribution network is still passive. Since the generation units grow and penetrate in distribution network, it opens more competition in electricity market. The liberalization and privatization of electricity market have been recently discussed. Similarly, any new market mechanism must not ruin the traditional system.

Another key point to accomplish the transition in sustainable way is a standard communication between all grid participating components. The standard communication is needed because DGs can belong to different owners and utilize various software/hardware systems. Therefore, international standards such as IEC and IEEE standards are important as a development guideline for the commutation system of future power systems.

In conclusion, the management strategy, control scheme and market model of conventional systems have to be cautiously studied in order to apply and adapt in a new strategy for future power systems. Furthermore, the communication system, which is a link between active components, is required to be standardized and must follow the international standard. Additionally, the different character between the transmission network and the distribution network has to be considered. For example, the symmetrical condition issue, it is obvious that the transmission network is basically described by symmetrical system, which cannot be directly implied in distribution system. The feed in power of DG unit can be operated as single phase systems. Those are different points from conventional power plant, which have to be taken into account in order to achieve the successful future decentralized power systems.

1.2 Problem Statements

The trend to move toward sustainable electrical power supply systems is decentralized systems based on RESs. As emphasized, any novel strategy for future power systems is necessary to consider about the coexistence between new integration of DG units and existing convention grid. Thus, a downsizing of conventional management and control process has been lately studied and promoted in [24], [25], [26], [27], and [28], where the power systems state variables control is the key point of those researches. Since the power systems stability issue is assured through state variable control, which allows further advance application e.g. the reversion of power flow process and the smart energy trading function.

However, there are differences between transmission network and distribution network, which are usually not considered. The most different point is a symmetrical condition of network. The network construction is worthy to point out that the transmission systems can be considered as a symmetrical network, which cannot be completely implied in distribution network. Moreover, there are different distribution network characters in some country. For example, the distribution network in Europe can be described by the symmetrical network [29], but the distribution network in other countries e.g. Thailand is totally asymmetrical system. This is obvious due to network construction, since the multi-phase systems are utilized in power distribution and the overhead power lines are untranspose [30], and [31]. Furthermore, the load characteristic, star- and delta connection can also cause the unbalanced condition. Regards those mentioned issues, the asymmetrical problem becomes more obvious in distribution power systems.

According to integration of DG units based RESs into distribution network, which may cause and expand stability problem into the symmetrical systems. Germany can be a good example for that fact. Typically, the nature of German distribution network can be described as symmetrical systems, since the network construction is described by three phase systems and the isolated underground cable is mostly used [29], but during last ten year the installed capacity of photovoltaic systems is dramatically increased in the statistic of 2012, and around 90% is installed in distribution network [32], [33], and [34]. It means that a maximum voltage increase could be occurred at very high photovoltaic installation area. Moreover, the photovoltaic system up to 4.6 kW is allowed to feed-in, but for a single phase feed-in only [35]. Due to that fact, it can eventually increase the unbalanced condition problem. To avoid the unbalanced problem, the maximum capacity for single phase feed-in must be limited [36], or three storage systems are required and separately connected to each phase [37]. Those mentioned solutions could be solved. Nevertheless, the solution of future power systems requires the flexibility and adaptability. Therefore, the unbalanced or asymmetrical condition problem is worth researching in order to deliver the sustainable solution.

In summary, the asymmetrical character of distribution network and the high share of DG units based on RESs can be the most important problem in future power systems stability. Furthermore, the liberalization of energy trading, which is expected in the future systems, can lead to asymmetrical problem as well. Consequently, the solution for future power systems e.g. power systems management and power systems control must be able to handle with asymmetrical problem, and it must coexist with the conventional process as well.

1.3 Motivation

To move toward sustainable electrical power supply systems, this express a large field of research. Plenty of research projects have been established. The clustering power systems approach is also included; this approach has been introduced and successfully promoted by the department of Power Systems and Power Economics, at South Westphalia University of Applied Sciences, Soest, Germany [38]. The main idea of this approach is to structure power systems network and to implement control application down to local network area. Furthermore, the coexistence between DG units and conventional power systems is also the target of the development.

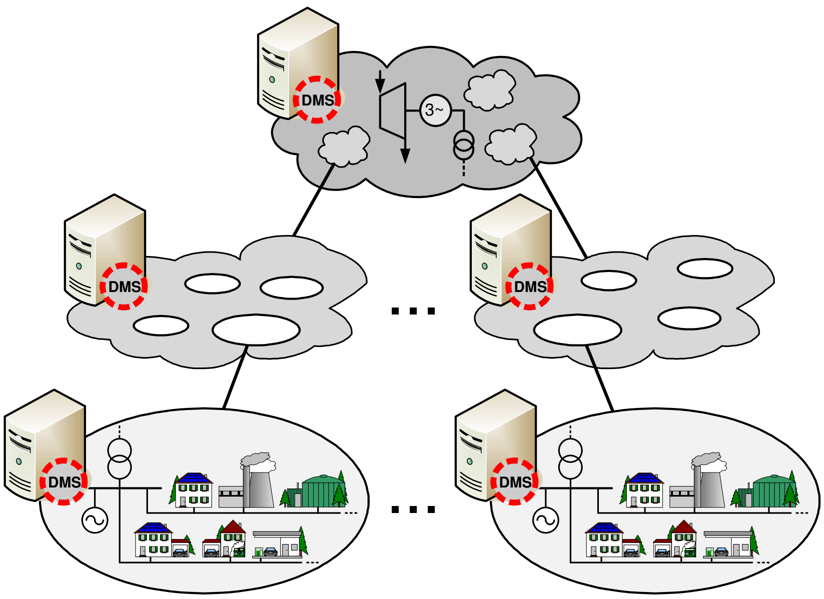


Fig. 1.3: Overview of clustering power systems approach [38]

The cluster network structure kept the main idea of European Network of Transmission System Operators for Electricity (ENTSO-E) interconnected grids [39], and [40]. To illustrate the cluster system network, an overview of clustering power systems concept is displayed in Fig. 1.3. The clustering power systems concept is to cluster the power systems into several areas, called cluster area. This means that each cluster network structure, which links to another cluster area, can be described like interconnected grids. It can be noticed that the local area or prosumer unit is grouped and considered as the lowest cluster level. Consequently, the local area is a part of another cluster level and this process is repeated upward to conventional plants. This network structure process is called bottom-up approach. Further information about clustering power systems network structure is clarified in Chapter3.

Considering on proposed cluster network structure, it can simplify the complexity of the future power systems and provides the opportunity to classify network construction. Thus, the asymmetrical condition due to different network constructions e.g. multi-phase power systems can be managed in order to solve asymmetrical problem in an easier way. According to good network organization, it gives also an opportunity to structure and standardize the communication strategy for future grid [41]. Additionally, the approach of energy trading linearization can be more obvious. Each cluster area can be considered as economic cooperative, and hence the association of future electricity market can be clarified through clustering power systems approach as well.

However, all expected process of future power supply systems can be realized, when the distribution system is able to participate in grid control as conventional way. In order to turn the ordinary passive distribution system to be the active systems, the clustering approach announces the distribution management system (DMS) for a cluster automation application. In fact, the DMS approach is already promoted and utilized as a service platform to empower distribution systems [42], [43], [44], and [45]. Nonetheless, the application of DMS based on cluster concept is a cluster controller, which is in charge for cluster control and management and aimed to operate based on each cluster area. This controller is a media to downsize the conventional process to local area e.g. control scheme and management strategy. Further information about DMS applications are given in Chapter4.

To support the future electrical power systems which towards to DG system, the clustering power systems approach is the consequent development to follow the stepwise evolution of the historical centralized power. It is possible to execute an automated power systems control through a basic conventional power system control approach. Afterwards, the optimization, management and economic functions can be applied into the decentralized system. Finally, this proposed philosophy is one candidate of the best solutions for the future smart gird and automated management applications.

1.4 Research Aim and Objective

One of the main challenges in future power systems associated with Smart Grid is the evolution process of the distribution network from passive system to active system according to grid control. This means that the distribution systems operator (DSO) level has to be integrated into the active grid control. Consequently, many research projects are currently conducted and investigated in order to complete this target. The outstanding projects are further discussed in section 2.3. The clustering power systems philosophy is developed for this purpose as well. In the point of view of clustering philosophy, the active grid control in DSO level must be related to the grid code from transmission systems operator (TSO) [38].

The aim of clustering power systems philosophy is to extend operational functions in TSO level down to DSO level, [38]. Therefore, it is worthy to portray the grid operation functions based on TSO level, as shown in Fig. 1.4, [46]. It can be noticed in this figure that the grid operation is divided into three parts to simplify an explanation. Part1 is related to the dynamic power systems control. The control function is responsible for the control of state variables, frequency and voltage. Part2 contains the offline grid operation algorithms. The main functions are the optimization tools for the power dispatch and the grid voltage observation. Those functions determine the reference values for the dynamic grid control in Part1. Regarding the active power dispatch under the actual weather and load condition, the historical data is compulsory as a reference. Hence, the information of weather data, load data, etc., is indicated in the third part of grid operation system, where those are stalled in a database system, as observed in Part3.

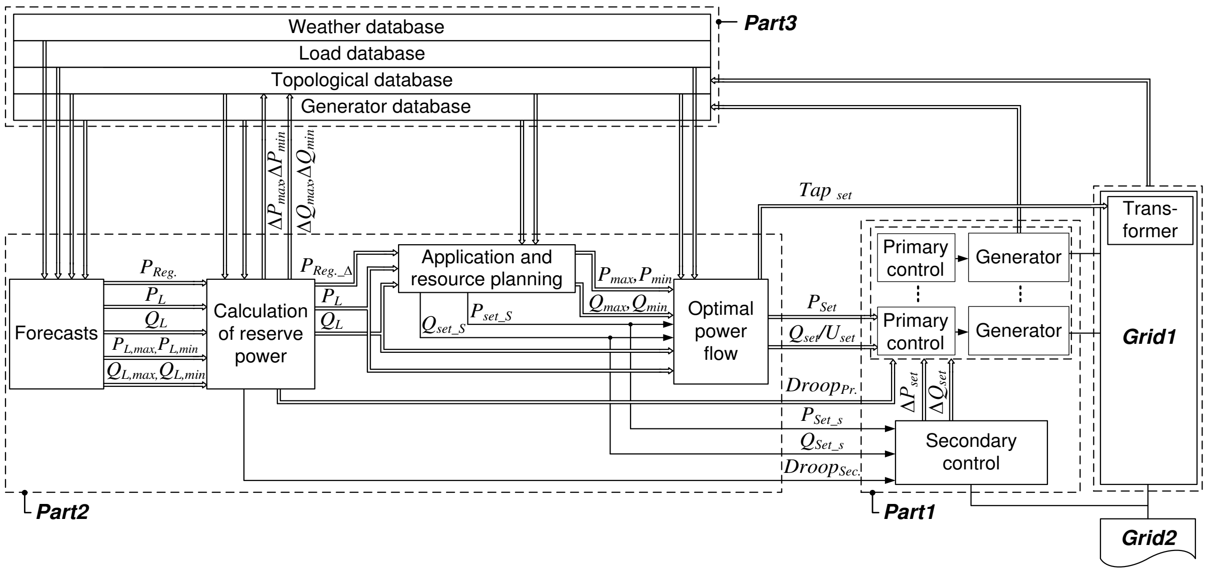


Fig. 1.4: Structure overview of TSO grid operation [46]

For the coordination of all different grid operation functions, the load flow calculation is essential. It is needed for observation and management of the line power flow in relationship with the grid voltage distribution. According to those functionalities, it can be pointed out that the load flow analysis is a fundamental function in the grid operation. Further detail of TSO grid operation system and exchanged variables between functions can be found in [46].

Considering the clustering philosophy with the aim of transferring the grid operation functions of TSO level down to DSO level, the approach of downsized grid control unit according to Part1 in Fig. 1.4 was already investigated. [47] and [25] show that the dynamic grid control functions, i.e. primary control (PC) and secondary control (SC), can be transferred in a cluster orientated way. The research works in [47] and [25] carry the remarkable results that the clustering philosophy give the fundamental structure for the application of PC and SC in the DSO level.

To reach the target regarding the transfer of the complete TSO grid operation functions to the DSO level, the functions from Part2 in Fig. 1.4 must be developed under the clustering structure conditions. As mentioned the load flow calculation is necessary for observation and investigation of the power grid status, therefore a cluster orientated load flow calculation method is required. This method has to fulfill the classical requirements of the load flow analysis under steady state condition. On the other hand, the load flow calculation has to satisfy the requirements of the clustering philosophy [38]. To accomplish the requirements of the clustering grid structure, the load flow calculation has to be provided for each cluster, in which the calculation has to be performed independently. In summation of all individual load flow calculations for each cluster area, the whole grid status concerning load flow and grid voltage distribution must be exactly represented.

The main aim of this thesis is to adapt the load flow calculation to the clustering philosophy, especially for the DSO level. Therefore, the special conditions of the DSO level, asymmetrical load flow, four-wire network, etc., have to be considered together with the independent system management strategy of each cluster area. As a result, this thesis is targeted to clarify the load flow calculation analysis strategy related to the clustering concept. A new approach for the cluster orientated load flow calculation is developed and introduced for special conditions in DSO level. Furthermore, the mathematical calculation algorithm should be simply implementable in decentralized Smart Grid management system. All those mentioned requirements have to be taken into account in the development process for the load flow algorithm, which can be done by minimizing the data exchange between the cluster areas.

In conclusion, the aim of this thesis is to evolve a mathematical system analysis method for the load flow calculation related to the clustering power systems philosophy, which the analysis method has to be separately calculated based on each cluster area. Particularly, the asymmetrical condition in distribution grid must be taken into account for the development of the cluster load flow method. Finally, the asymmetrical analysis method together with the clustering power systems philosophy will become a major application for enabling active power control and grid management in distribution network.

1.5 Research Contribution

To provide the sustainable solution of future grid, the clustering power systems approach has been developed and recently delivered as a sustainable strategy. It provides an intelligent network organization. The entire power systems are considered as the interconnected clusters. Regarding this concept, the interconnection points are only concerned for the cooperation between cluster areas. As a consequence, the downsized conventional control strategy can be implemented into cluster area. This leads each cluster to be operated based on each area and its process is identical with conventional system. To take this advantage, this research is studied based on this concept.

To operate the cluster control unit in an automatic way, the power flow analysis is necessary, as noticed in Fig. 1.4, [46]. Nevertheless, the clustering power systems approach can cause in the complexity of systems analysis, since the cluster network can be constituted by many interconnected grids. To overcome those issues, the main contribution of this research is to propose the power flow analysis method based on clustering power systems approach. The method has to be simple and robust. The analysis method including mathematical description are presented in Chapter5.

Moreover, the proposed power flow analysis method is aimed to solve asymmetrical network condition and unbalance feed in of DG units. Thus, the cluster system analysis under asymmetrical issue is one of contributions in this research as well. The power flow calculation technique and algorithm are stated in Chapter6.

In summary, the proposed cluster system analysis method is not only a key feature to realize the automated function of cluster control units but also the main function of the optimization, management and economic process, which are expected to apply into the decentralized system.

1.6 Dissertation Structure

This research proposes the power systems analysis based on the clustering power systems approach. The proposed strategy is developed stepwise downsize the conventional grid management system. It assists the automated function of cluster control units, which is a part of building and operating future smart power systems. To have an overview of this thesis, a dissertation structure is portrayed in Fig. 1.5, and a brief explanation of all chapters is shown as following:

Chapter 1 introduces the technical background of this research. The evolution of electrical power supply systems, key to successful future power systems, problem statement, motivation, research aims, research contribution and the dissertation structure are described.

Chapter 2 presents the state of the art of this research. To illustrate a vision of future power system, this provides an overview of recent definition and scientific research projects. The discussion at the end of this chapter shows a drive of this research study.

Chapter 3 elucidates the approach of clustering power systems, which is developed by the department of Power Systems and Power Economics, at South Westphalia University of Applied Sciences, Soest, Germany. This proposed strategy is clarified the way to active the entire power systems with a clear structure and in a simply way. The implementation strategy of downsized management system and control strategy to distribution network or local area are explained as well.

Chapter 4 introduces the proposed downsized control strategy based on convention hierarchical control method. The basic functionalities of control method and its application for future power systems are described. Furthermore, the proposed control method provides the possibility to automate the cluster area. Thus, the key to accomplish the automated management application is pointed out. To illustrate its feature, the simulation case studies and discussion are provided.

Chapter 5 proposes the key to successful in power systems management based on clustering power systems concept. The cluster systems analysis method is focused and introduced. A background of the utilized method, a hybrid calculation, is explained in order to illustrate an advantage of this method.

Chapter 6 focuses on the asymmetrical condition in distribution network. Consequently, the development of asymmetrical power flow calculation based on hybrid technique is pointed out, which is the main contribution of this thesis.

Chapter 7 provides the verification of hybrid power flow algorithm and the application of the hybrid analysis method through case studies.

Chapter 8 summarizes the research study and indicates the further works.

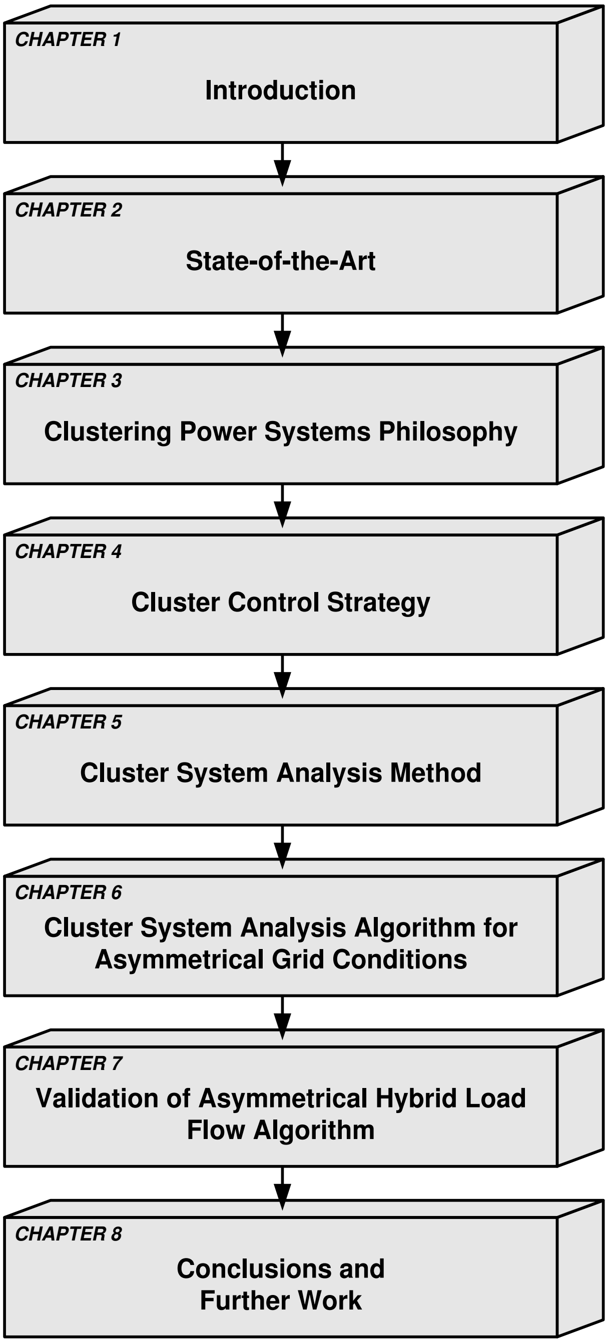


Fig. 1.5: Dissertation structure

2. State of the Art

This chapter presents the state of the art of the future electrical power supply systems. The current issues related to sustainable development are presented in order to illustrate the evolution of electrical power supply systems. Firstly, an electrical energy transition is discussed. This is a driving force to move toward sustainable power supply systems, since the global environmental problems become more significant. Secondly, the direction of future development is introduced through a term of smart grid and smart market because both of them are the lately worldwide research topics. Additionally, the future power systems requirements are also discussed to state the direction for sustainable development. Obviously, outstanding scientific research projects are selected and portrayed in order to show the trend of the future grid. At the end of this chapter, a summarization based on different aspect of research projects has been pointed out to compare with the proposed philosophy.

2.1 Electrical Energy Transition

Due to rapidly climate change and environmental problem, the response is needed to start the way to protect our world. One major cause is from the current power plants, which are the burning of coal, oil, and gas. They obviously ruin the global environmental. Moreover, the risk of nuclear power plant is also consciously studied. It might be more disadvantage than advantage, e.g., the Fukushima incident. According to mentioned problems of current power supply systems, the electrical energy transition has been focused in order to reduce and phase out the coal, oil, and nuclear power plant [48]. Therefore, renewable energy resources are taken into account as a key point of a low carbon society. To support that change, “Europe 2020” is a very good action. This project is a 10-year development strategy proposed by the European Commission on 3 March 2010. The main targets to accomplish by 2020 are 20% greenhouse gas emissions reduction compared to 1990, 20% of energy from renewables in total consumption, and increase of 20% in efficiency [49]. To emphasize this aim and move forward, the European Commission has also announced the low carbon Europe project, “Energy Roadmap 2050”, on 19 December 2011. The commission is committed to reducing greenhouse gas emissions to 80 - 95% lower than 1990 levels by 2050 [50]. It is noticeable that the European Union is establishing the challenges of decarburization power systems. To meet the targets, the electricity production from coal must be reduced. A key to successful low carbon society is the technology and development of RESs [51]. Huge investment and research projects based on RESs grid integration strategy are subsequently blowout [52]. Moreover, the efficiency of power electronic is dramatically increasing. Consequently, an inverter becomes one of key roles, and gives more possibility to integrate RESs into electricity network.

To indicate growth of renewable energy, the current progression on renewable energy in EU27 is selected to discuss. As mentioned that one of the main targets for the EU is to be reached by 2020 is a share of 20% renewable energy use in gross total electrical energy consumption. Thus, share of renewables in gross total electrical energy consumption is one of the headline indicators. In 2011, the average of energy contribution from renewable sources was estimated around 13.0% of gross final electrical energy consumption in the EU27, which has been increased around 5.1% from 2004. Whereas the consumption in some countries has almost reached 50%, some countries utilize around 4%. This big gap can be clearly seen in Fig. 2.1. It is worthy to mention that this data is provided by eurostat on 26 April 2013.

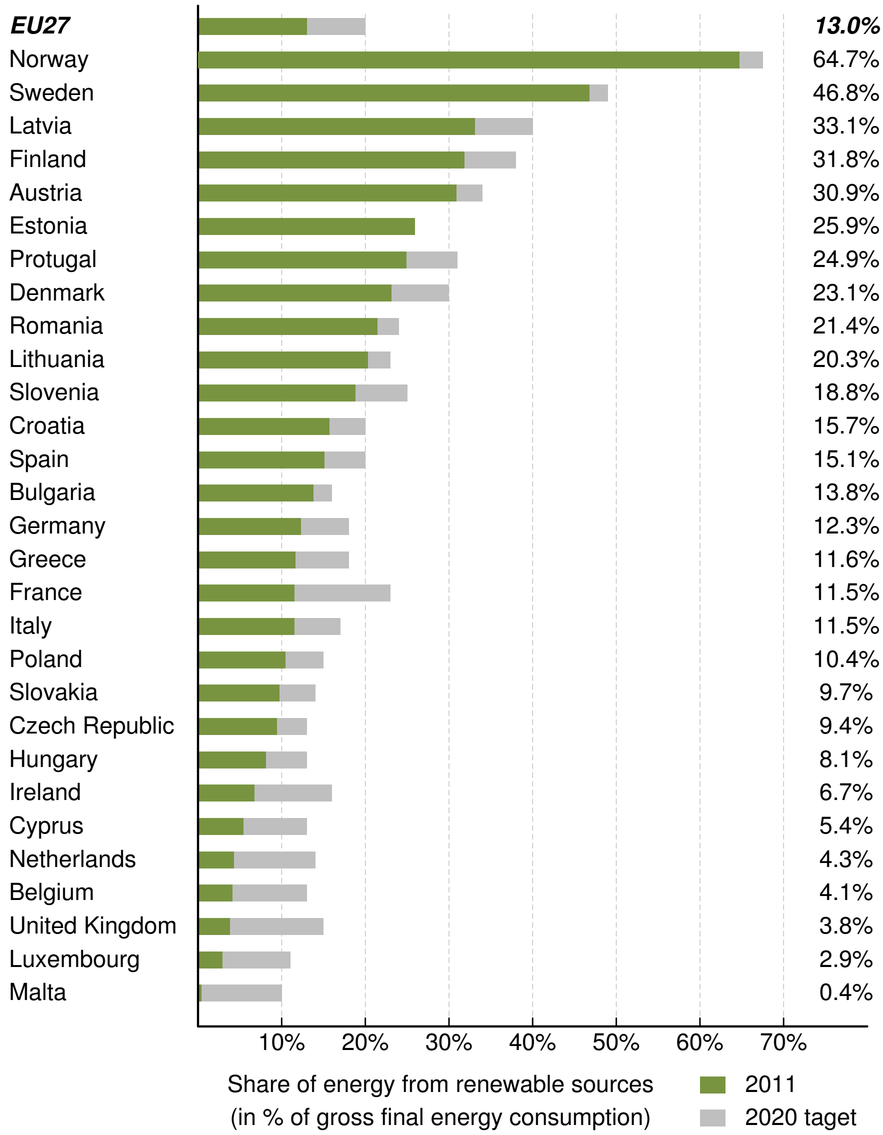


Fig. 2.1: Share of renewable energy in gross final consumption in the EU27, Norway and Croatia in 2011[11]

To reach the aim of low carbon city, “Energy Roadmap 2050,” it still needs a huge effort. For example, regarding Fig. 2.1, it is noticeable that ten countries have already reached the target of 2020, where the top three in share of renewable energy in gross final consumption are Norway (64.4%), Sweden (46.8%), and Latvia (33.1%). Conversely, there is also a big difference in share of renewable energy. Having a look on bottom three: Malta (0.4%), Luxembourg (2.9%), and United Kingdom (3.8%), this verifies and implies that the proceeding and developing is still needed in order to close this gap.

The transformation of electrical power supply system will not be happened overnight. The power plants, which will be utilized in coming decades, have to be planed and organized today in order to be ready for the transition in nearly future. The extension and improvement of grid has to be structured and prepared e.g. the bottleneck problem. In order to handle the future complex systems, the strategies and technologies have to be cautiously studied and clarified. Moreover, the growth of electricity cost has to be taken into account as well. The electricity market is also needed to handle the growing of electricity and penetrating of DG. Up to this point, it is obvious that the urgent issue, which is necessary to figure out, is the direction of future grid. Recently, the direction is discussed based on the term of *“Smart Grid”* and *“Smart Market”*. To have a big picture, the following section is donated for the explanation and the illustration of the interaction between both models.

2.2 Smart Grid and Smart Market

As many aspects to move towards sustainable electrical power supply systems, the responding is needed to start clarifying and structuring the direction of the future grid. The action time in order to build-up the sustainable electricity supply systems are now opening, since the energy conversion technology and the efficiency of grid infrastructure are dramatically increasing. Moreover, the penetration of distribution generation units in distribution network is also establishing the opportunity for the customer to be active for the electricity activity e.g. self-consumption. To take an advantage of new technologies, the vision and the concept of the grid evolution has to be setup. The objective must be able to ensure sustainable power supply by means of the energy efficiency, cost efficiency, safety and reliable system operation. To accomplish and realize those aims, the development effort needs to meet the principal aspects of the future grid. Consequently, the development aspects are expressed in bullet as following:

- **Improvement of generation and storage facilities**
  The development of renewable generation and distributed energy sources together with the storage systems will increase the efficiency of power generation. Obviously, this will allow the concept of decentralized power supply systems to be realized and will be able to serve the sustainable power supply systems.

- **Expansion and replacement of grid infrastructure**
  To support the improvement of the generation units, the grid expansion as well as the replacement of aging infrastructure must be taken into account. Since this issue is improved, the operation and efficiency of the existing infrastructure, and developing novel concepts, technologies, and smart applications are able to be accomplished. For example, the installation of new distribution transformer to be ready for reversion energy flow process.
- **Development of energy resource interfacing unit**
  The energy converter is one of the most important units for the grid integration. Recently, the power electronic device technology is dramatically improved. This will enable the development of grid integration unit in order to obtain the maximum advantage of energy sources. Furthermore, this will be a key element for the implementation of advance control strategies.
- **Power systems control strategies**
  Lately, the trend of decentralized power systems has been considered as sustainable energy supply systems. This increases the grid integration ratio of DG units. According to this fact, it can be pointed out that the distributed energy resources (DERs) are expected to be a key element in future power systems. In order to deal and obtain an advantage of DG units, the development of future-oriented control strategies and architectures is necessary step to ensure the stability for decentralized power systems approach.
- **Information and communication technology**
  Due to the implementation of smart infrastructures, it will bring the complexity in the term of grid operation. Consequently, the information and communication technology (ICT) based technologies for network automation comes up in order to empower the safety and reliability of the system operation. Since the intelligent infrastructure will be developed from different platform or company, the standardization of communication protocol must be announced. Furthermore, the new measurement technology leads to production of massive information. In order to handle with this issue, the data processing capability and the visualization tool are needed as well.
- **Enabling the participation of customer**
  Through the mentioned developments, it will also enable the new role of customer to be a prosumer. The prosumer will have a possibility to participate in the systems operation by offering their loads and storage capability as a consumer behavior or can produce and supply the energy by its own generation unit, e.g. photovoltaic systems, into the network. Moreover, the prosumer application is able to execute the economic function. It opens the liberalization opportunity of wholesale electricity market, since they intend to operate their own energy usage and to obtain the maximum cost efficiency.

Regarding the development guidelines, they will improve the conventional network including existing grid. The information and advance control strategies will turn the conventional grid to be smart. According to this point, it is noteworthy to mention that the transmission network can be already implied as smart network, since many appropriated and powerful application have already been existed, e.g. monitoring of power flow and information service from DSOs to TSOs. The core developing issue for transmission network can be mainly focused on grid expansion in order to support the growing of energy capacity e.g. offshore connection. On the other hand, the distribution network has to be fully upgraded to become smart by adding the development approach as shown in guideline. The communication-, metering-, control- and automation technology will enhance quality, efficiency and capacity of the distribution grid as well as the entire grid. Consequently, the entire conventional grid will be turned to be the *"Smart Grid."* Through those smart development approaches for the entire power systems, the target of sustainable power systems becomes more obvious. One of the indications stating the improvement of electricity grid is the penetration of RESs in distribution network.

Since the DG based RESs approach is successful, this leads to active electricity market application. The penetration of DG units in distribution network drives the customer to be able to involve in providing or purchasing electricity. This can be implied that the customer can select the utility in order to earn more benefits from providing or obtain the best price for purchasing. Based on this fact, the *"Smart Market"* term is evolved in order to handle the liberalization of energy market.

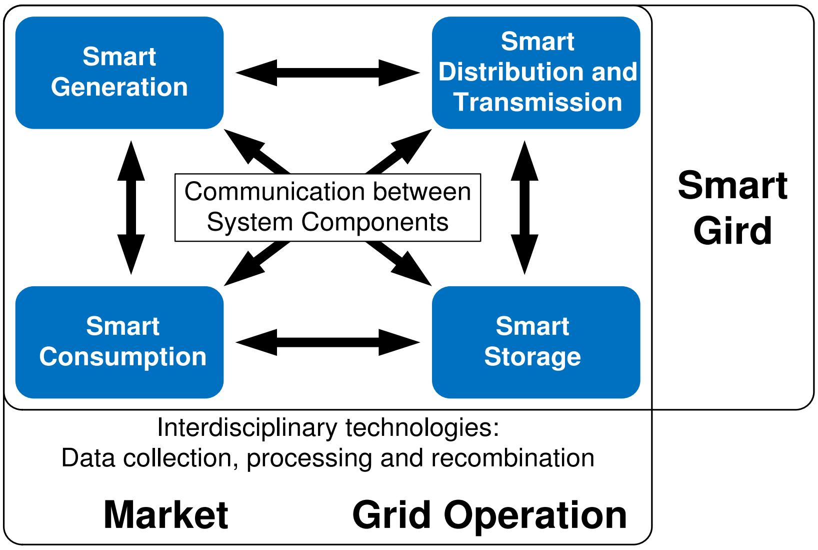


Fig. 2.2: Action matrix of smart gird [53]

In summarization, both *"Smart Grid"* and *"Smart Market,"* are a key issue to move towards future power supply systems. To contribute an intelligent solution for future systems, it is important to consider on both part: technical and economic part. Therefore, the interaction between principal aspects of both terms is pointed out. The action matrix between smart grid and smart market, which is introduced by DKE German Commission for Electrical, Electronic & Information Technologies of DIN and VDE in the cooperation with E-Energy, is selected for the explanation, as illustrated in Fig. 2.2, [53]. Regards the figure, it provides the clear vision of future grid player as well as their interaction.

According to Fig. 2.2, it is noticeable that the ICT is the major part as a communication media to interact between each player; additionally, to become a player of smart grid, each component has to be smartening as well. Thus, the classification of smart elements is taken into account. Their brief explanations are stated as following:

- **Smart generation**
  DG units have been taken into account as a future power generation and its technologies are becoming potential contributors of electricity supplied to electric utilities. This results in a high penetration in the grid of DERs based on RESs, e.g. wind turbine convertor systems and photovoltaic systems. Consequently, their grid interfacing unit, namely inverter, has been improved regarding the increase of the power electronic efficiency. These interfacing units open the gate way to other elements. Furthermore, the implementation of new control strategies and methodologies to inverter will empower and allow the smart generation. Finally, the DG units not only are power generation but also play an important role in network control.
- **Smart distribution and transmission**
  The electricity network operators, transmission system operators, distribution system operators are the important stakeholders for the deployment of future grid. In the future, they will allow the establishment of new market places. As energy service companies own the grid infrastructures, thus, they are a center of information communication between stakeholders [54]. Furthermore, they are responsible to undertake necessary investments to guarantee high levels of power quality and system security.
- **Smart storage**
  Besides the development of DG units and their grid integration, the storage system is also an ongoing improvement process. The operation of smart storage will be able to avoid or solve the fluctuation problem of RESs. The smart storage must choose a non-peak time for charging process. On the other hand, it is able to inject the electricity into the network during peak consumption hours. Additionally, the new electric vehicle technology is pushing the advances in smart grid. The EV's battery can play the same role as smart storage in distribution level.

- **Smart consumption**
  Behavior of smart consumptions or grid users can be described as generation unit, storage unit, or normal consumption unit. Therefore, they can manage the usage of their own energy. Moreover, they will have the ability to sell the electricity back into the grid, and they have the right to choose their suppliers to earn more benefit. As a result, it can be implied that the smart consumption is one of the important market players in future.

Regarding Fig. 2.2 and mentioned smart elements, it can be realized that the smart grid is a drive factor to establish the functionality of grid operation and electrical energy market. Concerning electricity market point of view, the data collection and processing from the elements are necessary. The smart metering is lately become one of important issues; collecting billing data, market demand and regulatory can be observed. This evolution of conventional grid will lead to moving from centralized generation to distributed generation, executing the power systems automation and enabling new strategy for electricity market. Finally, smart grid, smart market and grid operation should be forced together to contribute and come out with intelligent solution. In order to illustrate the direction of grid improvement, the following section is stated for the discussion of recent smart grid research projects and the new approach for future grid.

2.3 Smart Grid Research Projects

To smarten electrical grid, it is not a short time process. Understanding of background is needed, and the development must be stepped wisely from historical power grid. An improving of power systems is already happening. As portrayed in Fig. 2.3, [55], it can be observed that present grid has been changed from the past; grid operation systems and power generation units have been spread out from the center.

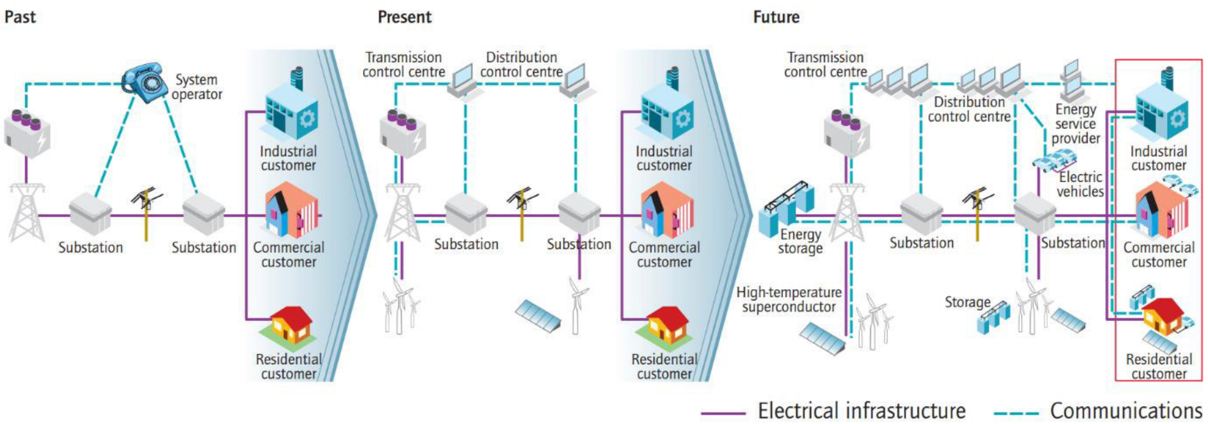


Fig. 2.3: Evolution of electricity grid [55]

Talking about an outlook of future smart grid, it must be stated that there are currently no final solution. Consequently, many pilot projects come up in order to demonstrate new electricity infrastructure, some circumstance solution, or full scale of smart grid technologies, which are deployed with existing grid. Having a look on a world leadership in an energy systems development, the Framework Programme of European commission has to be concerned. The European commission aims to forward an intelligent innovation and research in order to turn the current energy system into a more sustainable one. The present development projects are under the Seventh Framework Programme (FP7), which is in a period of year 2007 - 2013. The developments are mainly targeted to the grid integration of a diverse mixed energy sources in particular of RESs [56]. This will benefit to energy carriers and consumers through more energy efficient and energy costs in future. Furthermore, it will help to reduce the global climate problem, which will directly provide a great benefit to everyone. Since the FP7 is ended at the end of 2013, the European commission is already announced project Horizon 2020 [57], which is the biggest EU Research and Innovation Programme ever, started at the beginning of year 2014 to 2020. This framework is aimed to continue and forward current researches in order to accomplish the shared strategic objectives of Europe 2020.

To have an overview of the current development, this section is donated to present and discuss about the smart grid research projects, which are chosen from many outstanding researches. The selected projects are structured in the series of the power systems evolution. Based on evolution process, the main idea is subsequently transparent in order to show the trend of power systems development. Finally, a discussion based on those projects is provided. Advantages and disadvantages are distinguished; hence the direction of the future smart grid will be more obvious.

2.3.1 FENIX

In the past, the main objective of DERs grid integration was to inject the maximum active power into the grid. But with the increase of efficiency and high shares of DER units, they should in principle also cover similar control tasks compared with conventional power plants [58]. To overcome that challenge, the Flexible Electricity Network to Integrate the eXpected energy evolution (FENIX) project is launched. The FENIX research project was supported by the European Commission, under the 6th Framework Programme from October 2005 to September 2009. The FENIX is a very first project, which has been started the discussion about the future electricity grid concept. Consequently, the FENIX aims to design and demonstrate a technical architecture, as well as commercial and regulatory framework that would enable systems based on DERs via Virtual Power Plant (VPP) to become the solution for the future cost efficient, secure and sustainable electricity supply system. When DERs are aggregated into VPP, these groups of DER would have system visibility, controllability and impact similar to power plant in transmission level. This approach can be clarified through Fig. 2.4, [58]. If the VPP is connected to grid and its profiles are known, e.g. schedule of generating unit and operating cost, it can be implied that the VPP can be directly a market participant. On the other hand, the VPP can also provide ancillary services to grid e.g. active power / frequency control, and reactive power / voltage control. Therefore, the development of VPP concept is considered on commercial and technical activities [59]: Commercial Virtual Power Plant (CVPP) and Technical Virtual Power Plant (TVPP).

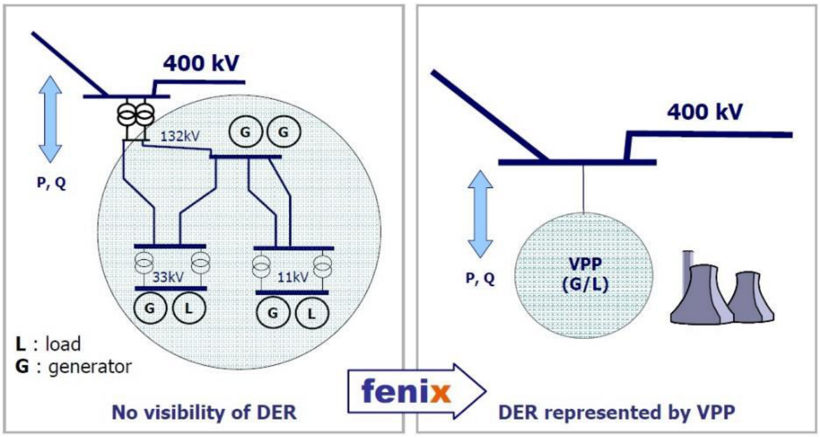


Fig. 2.4: FENIX VPP concept [58]

The CVPP is basically developed based on the market issue. The aggregation of the capacity of DERs units and the optimization of those units will forward the CVPP to be a part of wholesale electricity market. Then the main function of CVPP is to provide the representation cost and the operating characteristics for the DERs portfolio. Besides the commercial issue, the technical issue is needed in order to manage and accomplish the request form market side. Consequently, the TVVP is in charge to collect the CVVP's portfolio and contribute systems management. Furthermore, TVPP approach can be considered as Active Distribution Network (ADN) operators [60], since it can provide ancillary services to other system operators. According to this fact, TVPP activities can handle the network control capabilities. With this TVPP capability, the DG units will turn the role and can join the grid control like centralized power plant.

As VPP concept enables a local monopoly and any additional active management responsibilities, it is important to show its interaction with existing conventional systems. This will clarify how CVPP and TVPP are implemented. In order to figure out, Fig. 2.5, [58], illustrates the respective roles of the CVPPs and TVPPs including TSO in context of entire system interaction. The CVPP is basically operated in the energy markets. It optimizes its portfolio based on the reference of the wholesale markets. Then, it passes belonging DER schedules and operating parameters on to the TVPP. The TVPP is involved in local network system management as well as aggregating DER with local network parameters in order to transfer and present to TSO at transmission level. This can subsequently be used for balancing services, which TSO has to evaluate together with other offers or requests from other interconnected transmission systems. According to this scenario, the cooperation of TVPP and CVPP enables the DERs unit to join the transmission systems as a commercial and technical player. Individual DER gets a benefit from market, since it is able to gain access and visibility across all the energy markets. Additionally, the system operation also gains benefit from optimal use of all available capacity in system.

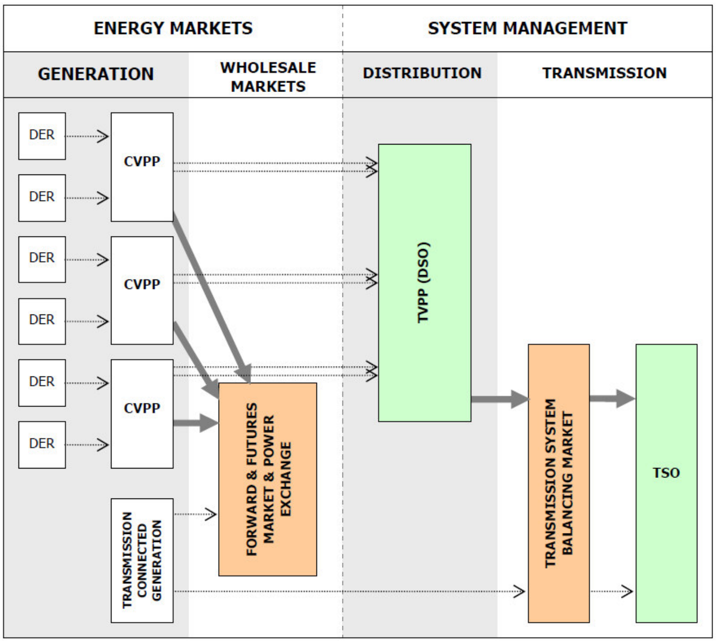


Fig. 2.5: CVPP and TVPP in system and market concept [58]

2.3.2 ADDRESS

The Active Distribution network with full integration of Demand and distribution energy RESourceS (ADDRESS) project is a five-year large scale project, which was supported by European Community's FP7 and launched from June 2008. The ADDRESS project has been come up with the campaign “add flexibility, add reliability, add accessibility and add economic into network”. Thus, this project is aimed to establish an active participation of domestic and small commercial consumer in order to be able to serve the future power systems and to obtain the maximum benefit from active demand (AD). AD has been pointed out as a key of future smart grid as well as distribution generation approach. It supports the development of DG units based RESs through the flexibility and provides economic benefits for all the participants. Therefore, ADDRESS is oriented to develop technical solutions both at the consumers’ premises and at the power system level in order to enable AD and to allow real-time response to requests from markets and/or other power system participants [61]. To realize the AD concept, the proposed architecture has been developed, which is considered and taken the advantage from FENIX project. The VPP is basically the idea of ADDRESS's aggregation concept [62]. To understand the concept of this project, The ADDRESS systems architecture is illustrated in Fig. 2.6, [63]. As regards system architecture, it can be noticeable that the project concerns market part (energy box, aggregator, market and contracts) and technical part (MV-LV transformer and substation). Their explanations are stated as following, respectively.

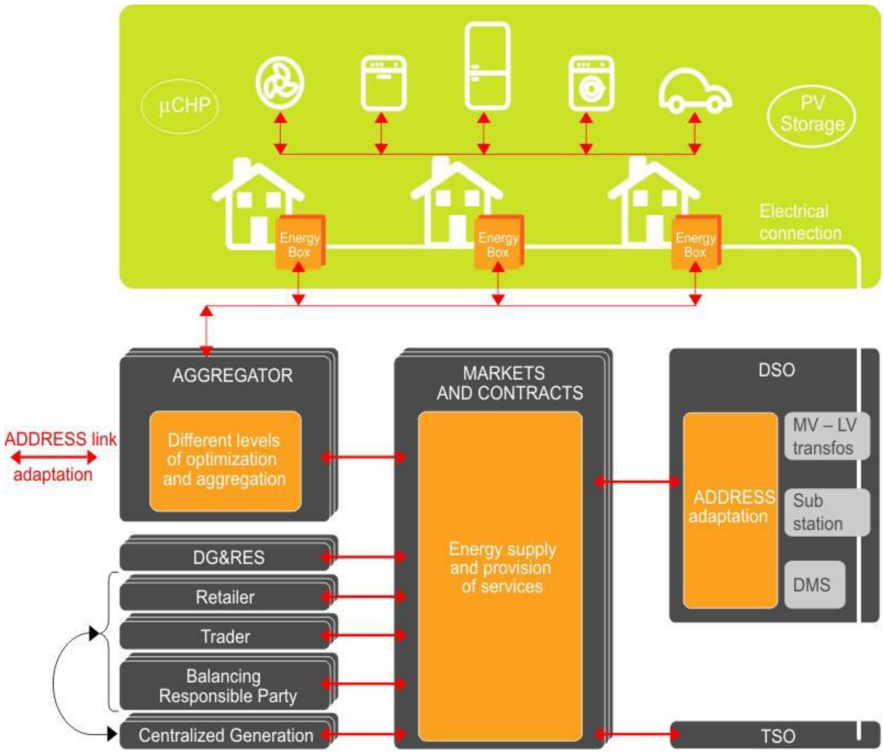


Fig. 2.6: ADDRESS system architecture [63]

Firstly, the market part is taken into account. As mention that AD concept is generally based on VPP approach. Therefore, aggregator is announced as a central key of AD. It is the mediators among the consumer, the market, and the other power system participants. It is in charge to collect the information of AD and be able to provide the optimization information to AD. Furthermore, the aggregator has to deal with markets and contracts in order to obtain the best offer and the agreement from DSO or TSO. The summarization of market process is detailed on [64]. The other key element, which is an interface of aggregator, is energy box. The energy box is essential element at the customer side in order to enable the AD potential. It carries out the optimization and control opportunity to connecting elements e.g. load and local DERs. To ensure information exchange between various participants, the ADDRESS has selected common information model (CIM). It provides a compatible interface for all information exchange. The communication methodology can be found on [65].

Secondly, the technical part is considered. It is obvious that the DSO plays an important role. It will be acted like intelligent distribution control center in order to manage AD. The three main services, which are expected from intelligent DSO, are voltage regulation and power flow control, tertiary active power control and smart load reduction [66]. Thus, the new control functions and intelligent infrastructures are required at DSO level. The distribution transformer has support the automatic voltage regulator (AVR). Subsequently, different strategies for voltage regulator and power flow control are needed. Moreover, the network analysis tool is also important; its function should cover the real-time and the offline analysis. All mentioned functions are basically existed in TSO. According to that fact, TSO is required only the communication link to the lower operator. On the other hand, it can be implied that new structure of DSO control center requires the interface to other DSO and TSO in order to execute the operation functions and services in the same time.

In final state of this project, they have applied the AD concept in many fields of test scenarios to describe the conceptual architecture. It is a proof that the AD approach can provide the success on the commercial issue [67]. To summarize the ADDRESS project, it can say that the aggregator is a trader of energy market. To achieve this aim, ADDRESS has pointed out that aggregator has to handle with various functions, e.g. the function of consumer characterization, market offering, revenue and risk management, and billing. The market and contract is the unit to serve the negotiation between aggregators and in charge to set the prices structure. The intelligent DSO and TSO control center is the key to assure the power systems stability.

2.3.3 Digital GRID

The organization Digital GRID was established in September 2011 as a not-for-profit corporation in Japan in order to develop technologies to support the new vision of future grid [68]. Since the proportions of renewable and variable energy generation are dramatically increased, the Digital GRID has concerned that the current electricity grid cannot deal with this growing. It can be foreseen that the new way of electricity usage is required. Moreover, this project has mentioned about the network of future grid, which is considered and developed with the intensive and extensive interconnected grids. This can improve the network reliability through redundancy. On the other hand, the interconnected grids can also increase the risk of wide area failures due to unbalanced power problem. In order to take an advantage of penetration of RESs and move towards future grid, Digital GRID has stated that it is important to measure the power levels in the grid, and hence the power flow control is able to be controlled and managed throughout the highly interconnected grids [69]. Up to this point, it can be noticed that the original idea of this project has been pointed out through the inefficiency of the current grid architecture.

The proposed of Digital GRID concept is to divide large synchronous grid into segmented grids, called digital grid cell. Originally, the cell concept has been proposed and developed, where the grid cell is subdivided by voltage class [70]. Each cell is in charge to coordinate local balance, clear fault, etc.; further information can be found on [71]. According to fact, the Digital GRID is aimed to subdivide the grid into small or medium cell size, and each cell is connected together asynchronously. The key to accomplish the interconnected cells is Digital Grid Routers (DGR), which is a multi-leg IP addressed ACs/DC/ACs converters or back to back converter. Since grids cells are connected by DGRs, it can be implied that the exchange power among multiple cells can be controlled through the existing transmission lines, which can be named as digital grid lines.

Concerning the small cell segment, e.g. generators, batteries, even smaller home electronics, will have IP address and can be controlled by digital grid controllers (DGCs). The IP-based power control is commonly a unique identification. Therefore, it can be used for recording of each power transaction, and it is able to distinguish power flow schedule. In order to figure out the power transfer based on IP address, an example of power routing including required components is illustrated in Fig. 2.7, [68].

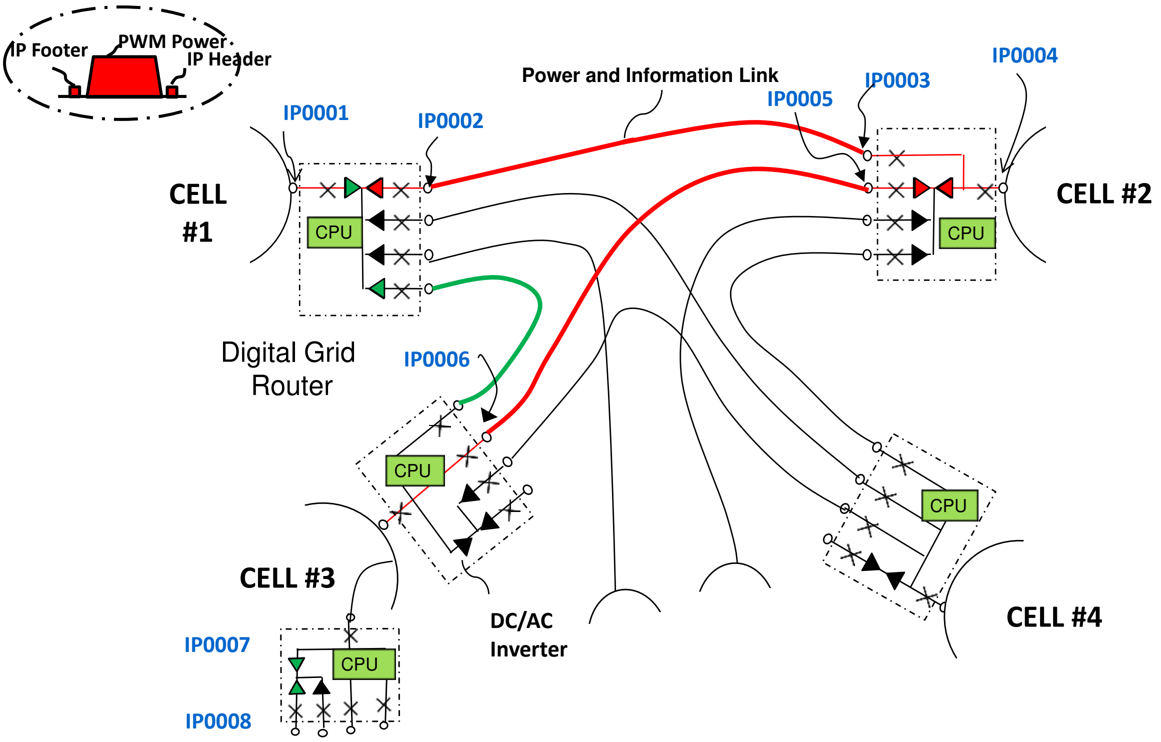


Fig. 2.7: An example of power routing [68]

As regards the illustrated figure, the features and functionalities of Digital GRID have been summarized as following:

- Independent cells are connected using DGRs. Each Router will have a CPU, memory and network communications. Those will be assigned the unique IP address. The communication is using an IP protocol like on the Internet based on the power line communication (PLC) approach.
- The control devices, DGCs, are used to transfer information and thereby to control power equipment such as generators and energy storage devices.
- In order to transfer the power, the power converter and the coordinated transmission lines have to be first selected by the IP approach. After that, the specified exchange electricity energy will be supplied directly through power converters to the end designation, which is selected first by IP address.

According to the Digital GRID solution, the grid control issue of the transmission grid is segmented to operate in the term of cell, and then it is able to control and schedule the flow of energy between interconnected cells. Moreover, this concept has been pointed out that all electrical devices could have IP address in a digital grid. This can be implied that it is possible to have a new business platform for power trading, called digital power trading because the power transfer between each cell is considered as a discrete power packet like a data transfer on internet [72]. In conclusion, it can be said that the Digital GRID is electricity grid, which has been inspired by internet.

2.3.4 ADINE

Active DIstribution NEtwork (ADINE) is the three-year EU FP6 demonstration project; it had been conducted from October 2007 until November 2010. The background of this project is oriented to the vision of smart grid, which its concept was resulted in many proposal e.g. VPP, micro grid, and power cell. It can be noticed that the vision of smart grid at that moment is focused on the distribution network. According to that fact, ADINE project is aimed to develop, demonstrate, and validate a new Active Network Management (ANM) method. The solution of ANM is operated as active components in managing the network to enable an easy interconnection of different DG units [73]. The solutions have been focused on the protection of distribution network, voltage control, and new generation of medium voltage STATCOM [74]. To have an overview of this project, the ADINE concept is illustrated in Fig. 2.8, [74]. It demonstrates the proposed control levels of distribution network and how the ANM method is affecting them.

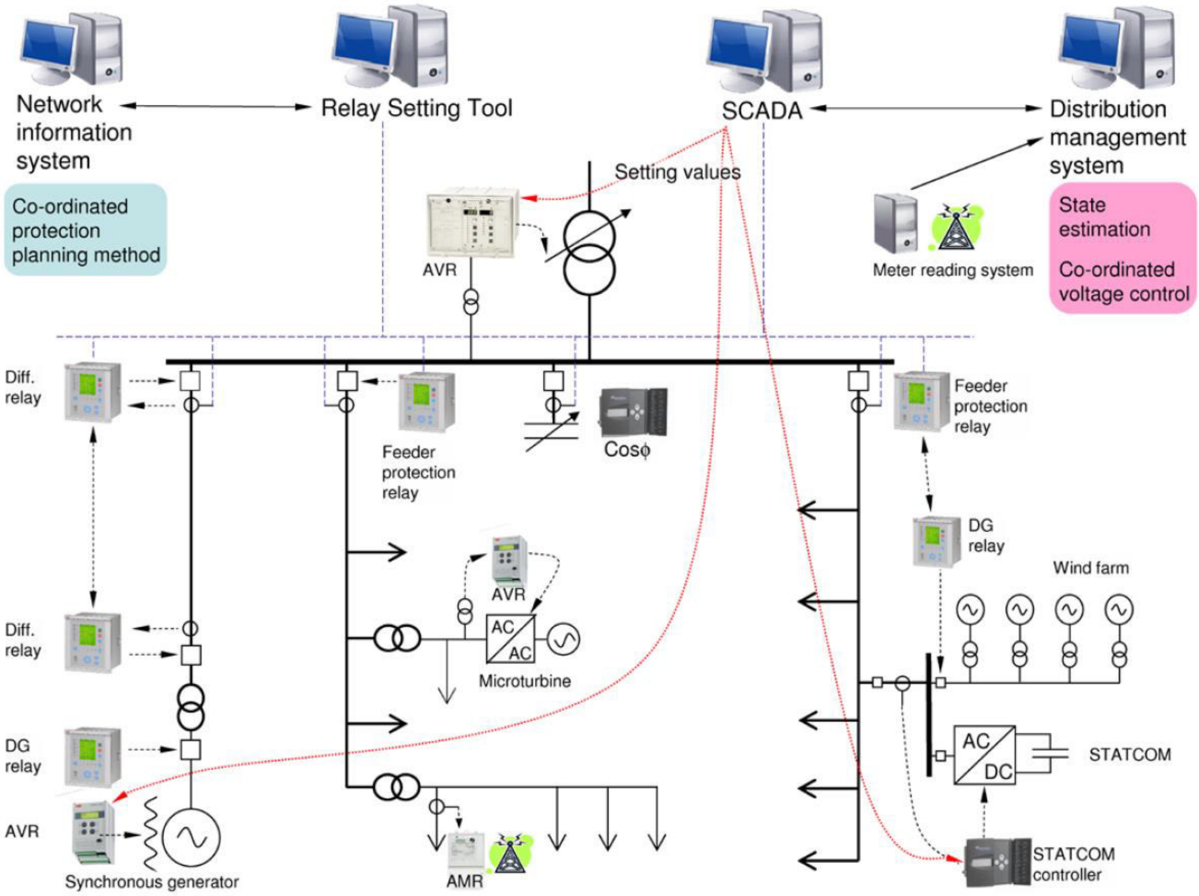


Fig. 2.8: Overview of ADINE concept [74]

The explanation of each project part is stated in the following: Since the advantage of DG units could be utilized for power systems stabilization or it provides the possibility to operate as islanding mode, so the DG units are equipped with loss of main (LOM) relay. In Fig. 2.8, it is described with DG relay. The ADINE project has demonstrated this protection issue through line differential protection intelligent electronic device (IED). The communication between IED units is utilized IEC 61850 GOOSE messages and Binary Signal Transfer (BST) of IED. The demonstration case can be found on [75]. Moreover, the ADINE also presents the DG protection planning method or the protection planning procedure. The introduced method is a center of the information collection of DG units and is a fault calculation platform based on network information systems (NIS). This can be noticeable in the figure as a relay setting tool. The planning procedure is detailed in [76].

According to voltage control issue, an automatic voltage regulation (AVR) is taken into account and directly implemented at DG units. In ADINE project, the power electronic converter is utilized and demonstrated with micro-turbine [77]. The simulation results and field test is a proof that the combination between DG units and intelligent converter is able to overcome voltage control issue. Even the AVR is able to handle, but it also needs the control center to provide the optimum control value for the controller. Consequently, ADINE offers Co-ordinated Voltage Control. This is operated as centralized voltage control center. Regards the concept figure, the voltage control algorithm is implemented in DMS that realizes also the system state estimation. The optimum controller value and information from grid is exchanged between AVR and DMS by using SCADA system. The field test results are illustrated in [75].

To increase DG's efficiency and improve voltage quality in distribution network, ADINE introduces distribution STATCOM instead of SVC because it offers wider working area than SVC. The development has been done based on DC/AC converter, which its function is capable of voltage control, reactive power control, power factor control, and fixed reactive power. The module overview and implementation test results are illustrated in [78].

To finalize the proposed elements and methods, ADINE has been validated and demonstrated the ANM solutions through real-time simulation environment [75], [79]. In conclusion, the ANM method improves the overall management of the electric distribution network including DG. This method is capable of ensuring safe network operation, increasing network reliability, maximizing the usage of the existing network and maintaining the required level of power quality. ANM method needs enabling solutions to support it such as protection, voltage and reactive power control, and planning and information systems of network. This clarifies the protection and automatic control system of future distribution power systems.

2.3.5 Web2Energy

The project Web2Energy (W2E) is funded by European Community's FP7 from October 2010. This project has been considered the effect and challenge of distribution network, which will involve the future grid or smart grid. To become smart supply systems, W2E has been pointed out three pillars of smart supply systems [80], distribution automation, smart aggregation, and smart metering. In order to track the objective of this project, three pillars are briefly explained as following:

- **Distribution automation**
  The target distribution automation is to ensure and increase the supply systems quality. For instance, any fault or disturbance in distribution network is generally consumed around one hour or more to allocate and clear fault [81]. This is very time intensive and cost. To improve that issue, the monitoring and control facilities are needed to install. Furthermore, those installations can be established the diagnostic voltage and load flow down to distribution level.

- **Smart aggregation**
  Regarding the development of DG units based RESs; the approach of VPP has been launched as mentioned before. The description of smart aggregation by W2E is subsequently expressed in the same way. According to VPP concept, the power generation can be scheduled. Afterward, it can play an important role in electricity market.
- **Smart metering**
  In nearly future, the end consumer will be involved in electricity market. Therefore, the smart metering or smart meter is taken into account a as key element. It has to be able to handle with various energy tariffs in order to obtain economic benefit.

To realize these three pillars of smart supply systems, it requests a data exchange and control center to optimize and handle [82]. Consequently, the ICT must be penetrated down to end consumer. It will be a data and management communication platform. Since the data communication model and service of communication protocol are developed from different vendors or companies, it is urgent to standardize this service [83]. Therefore, W2E is come up to overcome this problem. The W2E has selected and applied IEC 61850 for the power utility communication. Originally, this IEC 61850 standard is utilized for substation communication. Then it has been extended and applied down to consumer side, proposed by W2E. This results in the seamless communication of entire power systems. The overview of integrated usage of IEC 61850 from TSO control center down to end consumer is detailed on [84].

Since the communication strategy has been clarified in [85], the advantage of VPPs has been considered in order to realize the demand side management and demand side response concept. Subsequently, the W2E has announced W2E control center, as portrayed in Fig. 2.9, [86]. Regarding the figure, it can be found that three pillars of smart supply systems become obvious through W2E control center. In control center is consisted of three main parts: CIM-61850 converter is utilized for mapping measurement values between CIM and IEC 61850; CIM database contains all required data for monitoring and operation process e.g. plant rated power and meter value. Lastly, human machine interface (HMI) is provided for data processing, where the related charts and diagrams can be illustrated.

Combining all information from power systems, the approach of demand side management and response can be more transparent. The management activities will be automatically functioned, e.g. charge or discharge status of storage unit. Moreover, end consumers can obtain a service like energy tariff forecasting via mobile phone. As a result, they are able to compare and select the best offer.

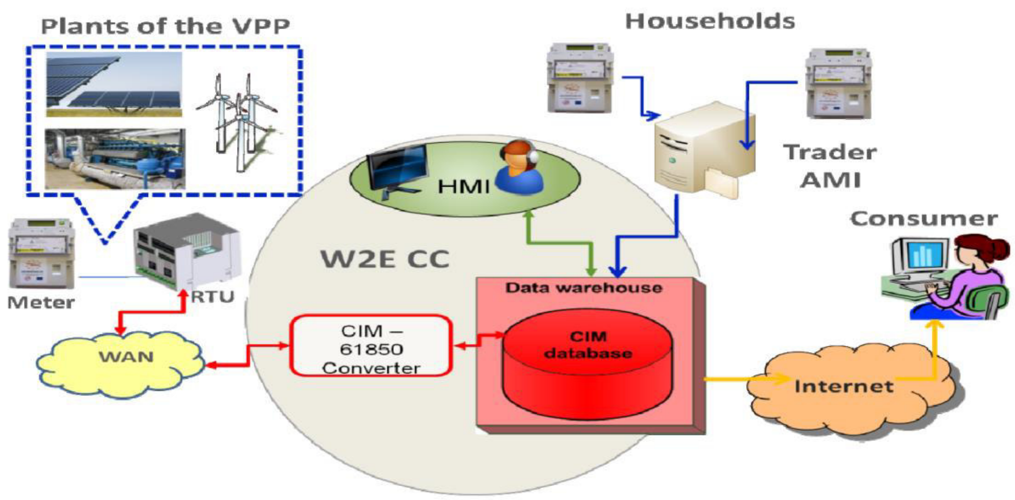


Fig. 2.9: System Architecture of W2E control center [86]

In summarization, the Web2Energy project presents ICT solutions for smart electricity distribution networks. It contributes the communication standardization to entire power systems by using 2 major standards from the NIST Smart Grid roadmap, CIM IEC 61968 and IEC 61850. The further study of IEC 61850 applications will be more discussed and illustrated through E-Energy project in next section.

2.3.6 E-Energy

The E-Energy program was acknowledged to challenge the future of the system in the campaign of *"Smart Grid made in Germany."* This project was aimed to involve the creation of an internet energy and energy market place. This can be implied that the intelligent grid must be transparent and automated function. Subsequently, the ICT has been pointed out to be a key to the conversion of power systems. For this reason, the E-Energy had launched six model regions in Germany (eTelligence, RegModHarz, EDeMa, Smart Watts, moma and MeRegio) in order to present the future grid solution [87]. The main target of those models is to demonstrate how the latest ICT can be applied and used to control the balance between supply and demand intelligently. According to that target, six model regions explore new control strategy, storage options and ICT infrastructure. This innovation will enable the decentralized energy generation units to connect and control interactively in the power grid, as well as the new electricity business cases.

Among those model regions, the Model City Mannheim (moma) [88] is selected for the discussion, since this project shows the way to active the participation of ADN and prosumer. Moma introduces the future of power systems control and management. A group of local controlled loads, decentralized generation, and energy storages is proposed for the network structure, and hence a cellular approach is utilized [89], its structure is illustrated in Fig. 2.10,

[90]. The cellular approach is targeted to provide a privacy and data protection for each single cell, i.e., house and business building. Data transfer, e.g. metering information, should be only transferred, when there is a request form another cell. In addition, cell elements have a possibility to be grouped, which can be acted like a micro grid cell and are consequently able to be grouped with central grid cell or distribution network. On the other hand, cells group can also decouple the failures cells; this result in improved efficiency and stability. Furthermore, the cell approach enables the individual tariff.

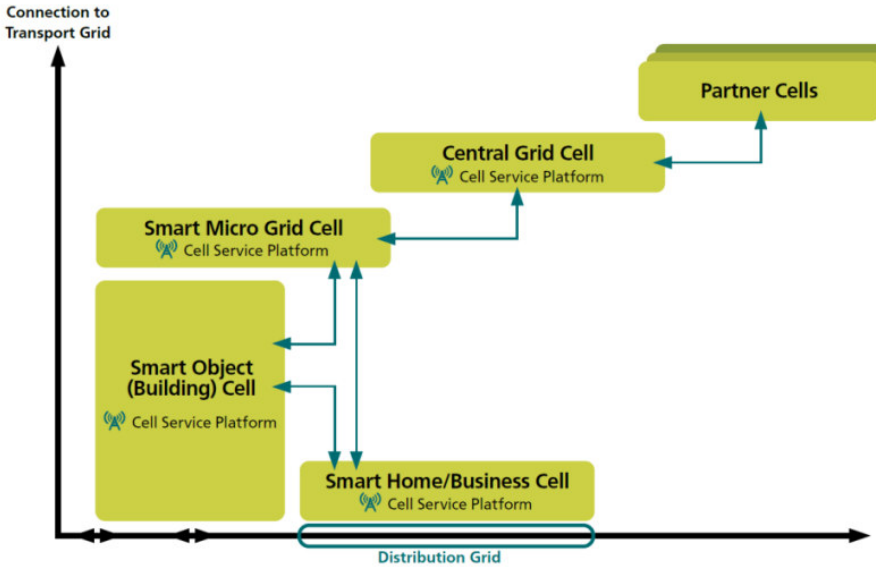
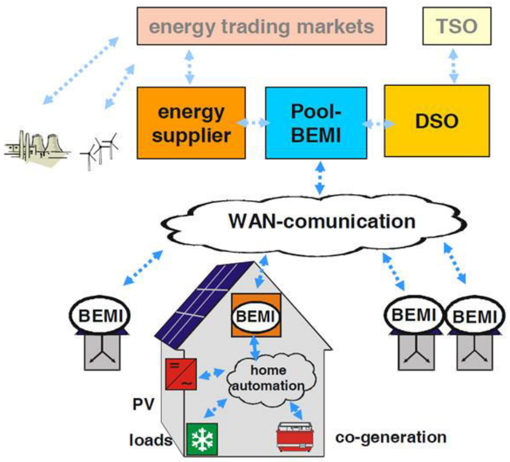


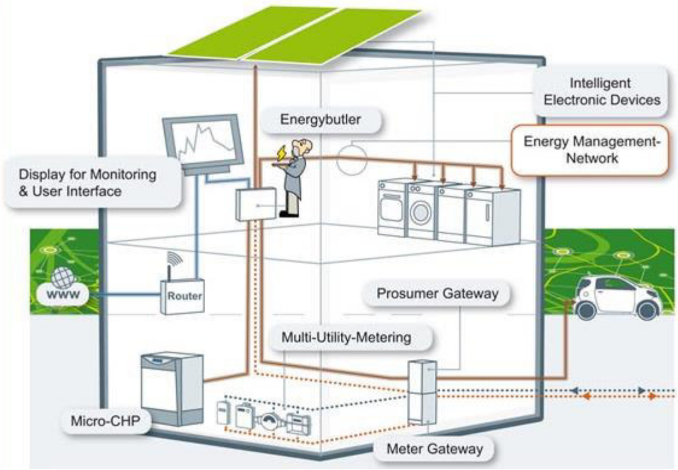
Fig. 2.10: Cellular system structure [90]

As cell approach is utilized, it should be noted that the cell's gateway is needed to clarify how to organize and manage the control signal from grid side and to cell side. The bidirectional energy management interface (BEMI) from OGEMA Allianz is therefore selected as energy management gateway [91]. Its concept is portrayed in Fig. 2.11.a, [89]. Basically, the BEMI is in charge to control belonging units. On the other hand, the aggregation of BEMI is expected. It allows the efficient economic agreement structures between cells and DSO or energy supplier, the pricing, customer behavior and etc. are predicted and managed; this action is donated by Pool-BEMI. Further information about BEMI can be found on [92], [93].

To enable prosumer action, moma proposed an "energy butler". This is an intelligent controller, which knows every device in house; it can manage, e.g. the best time for washing dishes, drying clothes, and etc. Moreover, it will ensure the energy production from renewable sources, since it may receive a forecasted data. As stated in Fig. 2.11.b, [88], the energy butler is a center for prosumer management. This developed technologies, BEMI and energy butler, are the key to establish economical operation of each cell. In order to achieve this proposed strategy, it requires fast and reliable interaction of all cells in the distribution network. The IP-based Broadband Powerline (BPL) structure is subsequently utilized in project moma, which allows Internet protocol-based data transfer in distribution grid. WAN-connection is also used for the data transfer to higher level, e.g. DSO, via other broadband media. This results in the internet of energy, presented by moma project. The overview of entire communication system is summarized in [91].



(a)



(b)

Fig. 2.11: a) BEMI concept [89], b) moma project concept [88]

In final state of this project, the proposed concept is examined in field test with 1000 participants. By using smart energy butler, the participants act like individual player in network. They can themselves regulate their energy consumption, individual decide when they want to buy, to sell, or to storage energy, since they can track the energy market. This is the realization of virtual market place.

2.4 Discussion

Obviously, the challenges of the future energy supply are the establishment of environmentally friendly, sustainable power systems. Those call the increasing electricity share from RESs and the evolution of the network infrastructure. Additionally, the electricity market issue is also concerned, since the DG units are dramatically penetrated in distribution network; this results in the liberalization energy market. To realize and enable the interaction between all intelligent devices, the ICT is finally taken into account as a media. Those mentioned issues are generally a basic concept of recent smart grid. According to those facts, many research projects are launched in order to demonstrate smart gird solution, as stated in the selected projects. From the discussed projects, they can be categorized into four groups:

- Grid and Market issue,
- Intelligent infrastructure,
- Information and Communication Technology solution
- Application field solution.

Firstly, grid and market issue is discussed. The projects which are related to this category are FENIX and Address. The FENIX is one of a very first development of the future grid network. The VPP concept has been launched based on commercial and technical propose. In fact, this approach has been initially developed based on commercial issue. The aggregation of many diverse DER creates the single portfolio for each aggregation area; this DERs portfolio is part of the future wholesale electricity market. This is also referred to the ADDRESS project, which takes the advantage from FENIX project concept. ADDRESS has expressed the aggregation approach direct to prosumer unit, this results in a full active distribution network. According to those two projects, it can be noticed that the aggregation approach is a base for future system network.

Secondly, the Digital Grid and ADINE are taken into account. Those two projects show the development of intelligent hardware, which leads future system architecture. The Digital Grid proposes Digital Grid Routers (multi-leg ACs/DC/ACs converters) as the key element to fulfill the requirement of future systems, e.g. independent ability of power flow management. Regarding this fact, the Digital Grid is aimed to subdivide the grid into small or medium cell size, and each cell is connected together asynchronously. This cell structure has been originally considered based on existing network infrastructure; furthermore, cell structure is organized based on IP address. The ADINE is another demonstration project that the target is to improve efficiency and voltage quality in distribution network. Therefore, ADINE introduces the novel distribution STATCOM, which its function is capable of voltage control, reactive power control, power factor control and fixed reactive power. Moreover, the protection strategy is also demonstrated as one of required automation solutions in distribution system.

It cannot be presently denied that the communication is the cornerstone of success in automation power system; term of ICT has been subsequently concerned as a solution, which must be penetrated down to end consumer. Unfortunately, it can cause a problem because of different communication protocol, and the agreement for communication standard in distribution network is not available. In order to figure out this issue, the usages of IEC 61850 are taken into account in W2E project. Traditionally, the IEC 61850 standard is developed for substation communication. Nevertheless W2E has shown the extension of this standard and its application down to consumption unit, i.e., smart metering issue. This project results in an example of seamless communication in entire power systems.

Finally, the pilot projects, proposing the solution of smart grid, are worth having a look. The E-Energy project is also included; it aims to involve business model of energy market place by showing how the latest ICT can be applied and used to control the balance between supply and demand intelligently. The moma project, one of six model of E-Energy, is selected for discussion. It portrays the prosumer solution. The BEMI and Energy Butler are the development key elements. The BEMI is energy management gateway to interact with other cell element. Energy Butler is the intelligent controller for home unit or cell unit. It can be noticed that cell structure is utilized in this project as well, and it has been implemented down to prosumer level.

Up to this point, it is obvious that the realization of sustainable energy systems is a huge work and still needs further development. It can be however summarized that the current direction of development is to fulfill the action matrix of smart gird, which is stated at the beginning of this section. The most interesting issue is the concept of VPP, aggregation or cell structure. As regards their application in distribution network, those three concepts, VPP, aggregation, and cell structure, can be implied that they are a fundamental strategy of future network. However, it can be noticed that they are originally developed from the same idea, grouping of DERs and improving them in market and technical term through intelligent infrastructure.

While, many research projects share and introduce the future grid solution through their point of view. It must be emphasized once more that any novel development has to be coexisted and must not make a technical conflict with the conventional grid. According to this fact, the proposed clustering power systems philosophy is evolved. It is obvious that the proposed clustering power systems approach is also introduced and targeted to smarten distribution network. But to close the gap between transmission and distribution system operation, the entire system operation must be conformed. Consequently, the clustering approach delivers a *"bottom-up approach strategy"*. This strategy is aimed the establishing of downsized conventional automated control function, i.e., PC, SC and tertiary control (TC) process, into any single grid unit or distribution network. Furthermore, the strategy also targets to provide the planning and organization system in order to find out the optimum value for control and management process of each cluster area.

As a result, the chance to achieve the automated cluster management and optimization in order to empower the distribution network becomes apparent. This will close the gap between transmission and distribution system operation and results the entire system operation in a unified electricity network from the lowest single prosumer unit to the highest transmission network. Hence, any active single unit or any active distribution area is able to join and participate with the conventional grid with the compatibility. In conclusion, this clustering power systems philosophy is aimed to structure, service and operate of distribution power systems in the same way as conventional power systems process. Further description of clustering power systems philosophy is described in following chapter.

3. Clustering Power Systems Philosophy

Moving toward the sustainable energy supply systems, the fundamental changes in the power supply systems are required in the technical, commercial and regulated arrangements of the electrical networks to ensure supply security, to increase efficiency and to guarantee social and environmental sustainability. Recently, the DG technologies become more potential contributors of electricity supplied to electric utilities. This increases the grid integration ratio of the DG units. Thus, the trend of decentralized power systems has been focused and considered as future of energy supply systems. Hence, some change in the decentralized systems can be predicted e.g. the energy flow process will be changed from unidirectional to bidirectional or rather the reversion of power from distribution level to transmission level. To be ready and support the change in power system, the distribution systems are consequently changed from a passive control area to be an active control area. Therefore, it can be implied that evolution of electricity grid results in a huge work, and they require a clear structure in order to achieve.

To clarify the direction of future grid, many large pilot projects have been developed to promote a solution for future power systems, as discussed in Chapter2. The clustering power systems philosophy is also another approach to realize the evolution in energy supply systems. As emphasized that any development for future system must follow the conventional power systems process; the system structure and the control functions of clustering philosophy are consequently developed based on the conventional system. This coexistence idea is a key of success in sustainable power supply systems. To figure out the proposed philosophy, this chapter is donated for clarifying the main idea. For instance, how a bottom-up approach and interconnected networks architecture can be flexible strategy to build up a clustering network, or why the application of downsized control functionalities is pointed out to be an essential control function to close the gap between transmission operation and distribution operation. Lastly, impacts of clustering strategy, including advantages and disadvantages are discussed. Before having a look on the proposed strategy; it is praiseworthy that the clustering power systems philosophy has been introduced and successfully promoted by the department of Power Systems and Power Economics, South Westphalia University of Applied Sciences, Soest, Germany [38].

3.1 Interconnected Transmission Grids

Obviously, the interconnected electricity grids have an important role in the energy supply system as a backbone for cross country energy transfer. The first international interconnections were built in Europe in 1906; they were a transmission link between

Switzerland, France, and Italy [94]. Presently, the interconnected grids become a large area, since the interconnections of neighborhood systems have been increased. A good example is European Network of Transmission System Operators for Electricity (ENTSO-E). In July 2009, TSO groups among European countries decide to establish ENTSO-E. This working group is one of the important interconnected grids communities. Currently, there are five regional groups in a synchronous grid, i.e. Continental Europe, Nordic, Baltic, Great Britain, and Ireland, as illustrated in Fig. 3.1, [95]. In fact, these five regional groups are not any new community; which can be recognized from the previous group, e.g., the Continental Europe was named as Union for the Coordination of the Transmission of Electricity (UCTE). In order to keep advantages and stability of former TSO associations, these five groups still continue their previous activities under ENTSO-E.

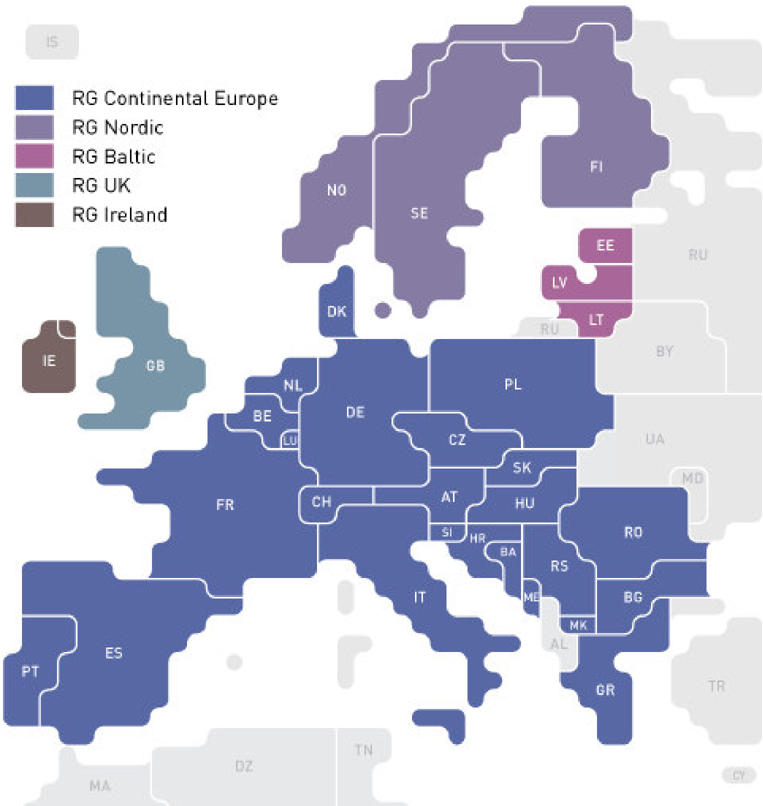


Fig. 3.1: Overview of ENTSO-E interconnected grids [95]

However, the harmonization between five system operators has to be cautiously concerned to ensure the whole interconnected grids reliability. Therefore, the ENTSO-E promotes and invests many development projects regarding network infrastructure, market, security, and energy policy to become a pan-European electricity network. One of the major projects is E-Highway 2050 project [96]. As predicted that high penetration of RESs, innovative active demand-side management, etc. will be realized in near future; E-Highway 2050 focuses on the planning and expansion of pan-European electricity network from 2020 until 2050 in order to ensure the delivery of renewable electricity as well as market integration. Another project, which is worthy to mention, is CIM project [97]. Regarding the communication issue, ENTSO-E has decided to examine on the data exchange format between system operators based on the IEC-CIM standard. The results and experiences from the studies will be utilized and published in future grid code as the standard of data exchange processes, and hence, this will ensure the compatibility between system operations. It is noteworthy to mention that the current grid code is based on UCTE grid code.

Up to this point, in order to discuss the TSO activities, the smaller scale of interconnected grids is considered. In Germany, there are currently four TSOs, which are interconnected their networks to neighboring networks via 380 kV and 220 kV systems. To have an overview, 50hertz is selected for discussion. 50hertz is one of ENTSO-E members, which is a holder of electricity transmission in northeast of Germany and interconnected with TenneT TSO GmbH in Germany, CEPS a.s. in Czech Republic, Energinet.dk in Denmark, and PSE S.A. in Poland, as shown in Fig. 3.2, [98].

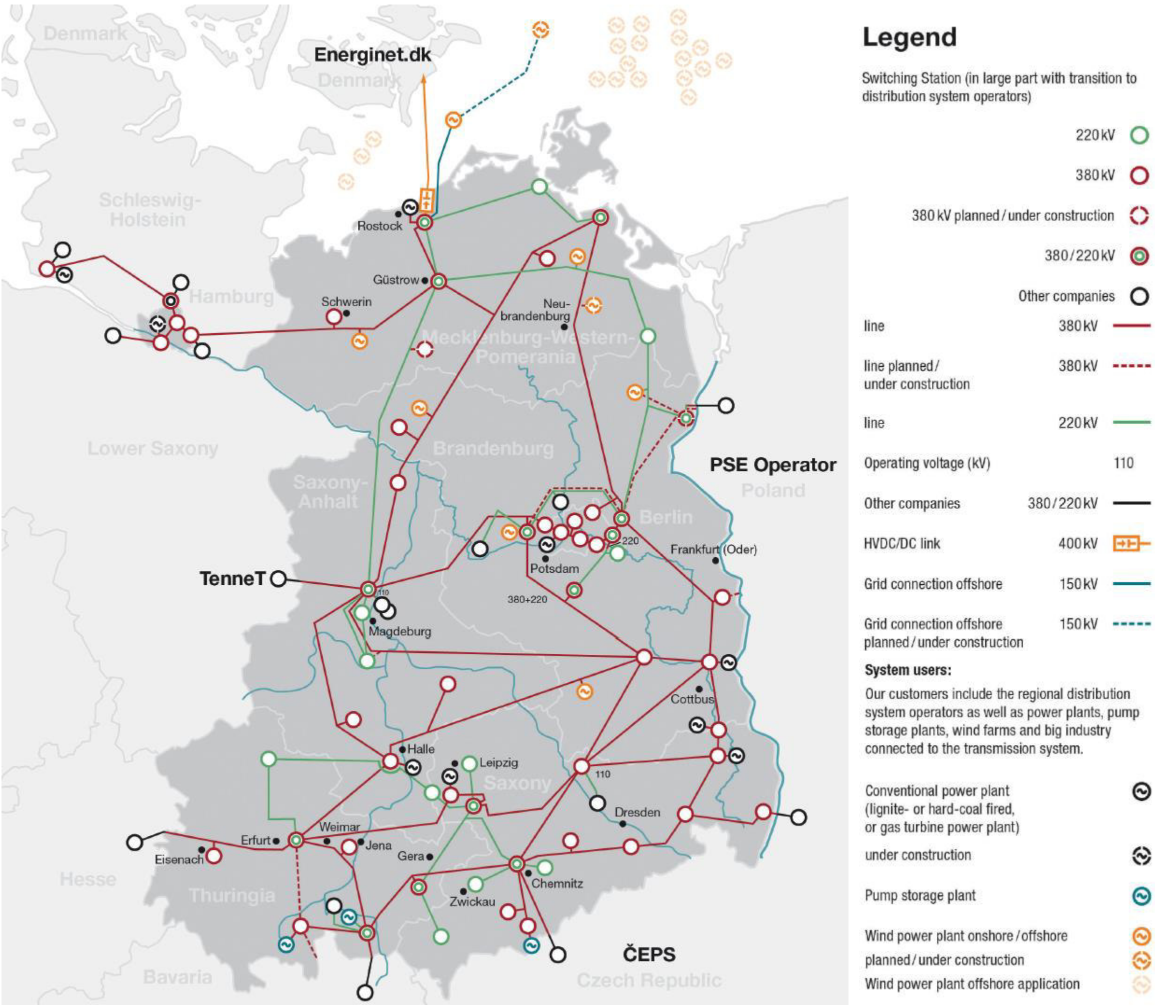


Fig. 3.2: 50hertz High-voltage grid map, December 2012 [98]

The main activity of transmission services is to ensure the energy transfer from power plants to DSO accounting areas and either export or import between cross-border links. These services are based on the power schedule agreement. The electricity quality is also another TSO service, which has to be concerned. There are technical tools to maintain electricity quality regarding ENTSO-E grid code, i.e. PC, SC, and TC. Their information for the control structure and application is detailed in the next chapter. Additionally, the mentioned tools are in charge to manage the network transmission capacity or active power flows. The dispatch control is able to achieve by means of TSO functions and activities. On the other hand, the TSO is responsible for grid expansion in order to avoid a bottle neck problem and support a new power generation unit, for example, the under construction grid connection to offshore wind park in Baltic Sea as noticed in Fig. 3.2. Based on the interconnected grids structure, it leads to significant improvement and reliability of energy power supply system. The interconnection enables the backup possibility. Parallel operating power plants can support each other in the case of power plant failures. Therefore, it can also refer to the maintenance schedules; permit planned outages of power plant and transmission system facilities. Moreover, the reserve capacity can be reduced by sharing reserves within the interconnected network. Accordingly, the interconnection results in an optimized management and dispatch in order to receive a low cost power generation.

In summarization, the interconnected grids are core of power supply systems. They operate safely, reliably, efficiently and economically to deliver and guarantee the power to customers, since the interconnected networks are basically developed to fulfill the technical and economic issues. To keep their advantages and to coexist with TSO, the proposed clustering power systems approach is consequently developed based on interconnected grids structure in order to forward the smart operation of transmission system to distribution system.

3.2 Clustering Power Systems Approach

Presently, the electrical power system is introduced based on transmission system and interconnected systems, which are the backbone of the current power systems. The interconnected networks are able to handle their services and operations in an automatic way as well as the interaction with neighboring networks. On the other hand, the main task of interconnected systems is electricity market issue. The energy can be transferred or exchanged regarding the commitment and schedule through interconnected grids. According to this fact of TSO, the requirements of smart grid, which are stated in smart grid action matrix, are already existed in the transmission network or rather the interconnected grids. Consequently, the interconnected systems can be implied as a model for future power systems toward distributed generation systems. To keep advantages of interconnected networks, the clustering power systems approach is basically developed from the characteristic of interconnected systems and proposed as one candidate of smart grid solutions.

Before introducing the proposed concept, the trend and the direction of future power systems regarding network structure and strategy are briefly reconsidered. As stated in Chapter 2, the term of VPP, aggregation, and cell are very often mentioned in many projects. If those terms are closely examined, it can be found that they are basically described based on the similar idea. Their strategies are aimed to group or collect DG units in order to create the generation profile. Even though the mentioned aspects are well developed and oriented to the active distribution network operation, this kind of operation must be strictly orientated on power systems stability as well as the power balance in each control area, which are typically forgotten [99], because this operation concept is mostly targeted on market issues [58] and [63]. Hence, the operational functions of interconnected grids are taken into account, since they provide compatibility between new system and the existing or conventional system, as examined in [100]. This is a great benefit, which is transferred to clustering power systems approach as well.

To achieve the coexistence with conventional power systems, the clustering concept proposes a bottom-up approach [101], as depicted in Fig. 3.3. The bottom-up is aimed to create network structure from the distributed low voltage levels upwards to the high voltage levels step by step. On the other hand, the bottom-up approach is the strategy for implementing the downsized conventional control scheme in distribution network in the way of DMS. Subsequently, the control architectures in distribution level are evolved based on the same control approaches in transmission system. This leads to the same structure and same operation in entire power systems. By this proposed strategy, the distribution system control is gradually conformed to the conventional power system control, and the aim of active distribution network is able to be realized as well.

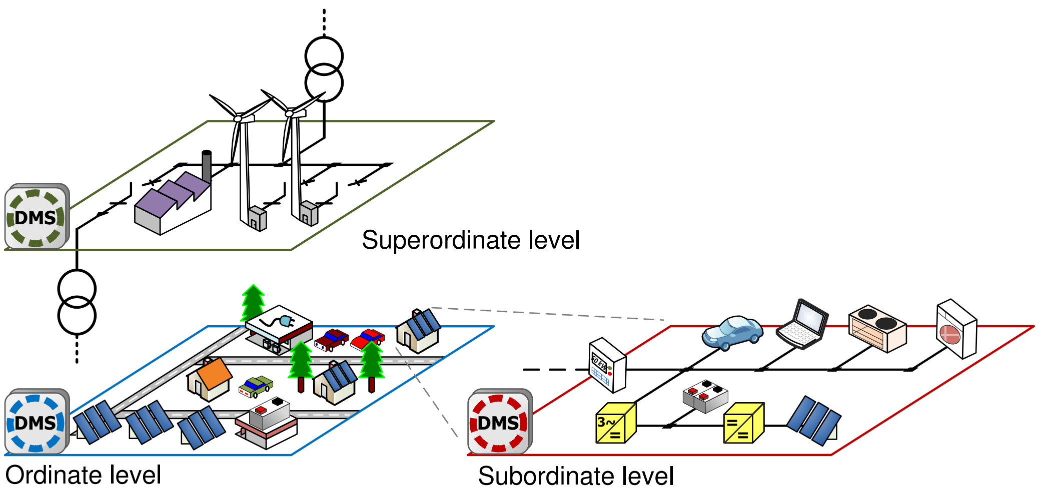


Fig. 3.3: Cluster network using bottom-up concept [101]

Besides the empowering distribution network with the downsized conventional control schemes, the bottom-up also results in multi-level approach [25]. A good example of multi-level approach can be described by interconnected clusters network, as shown in Fig. 3.3. Noticeably, the interconnected clusters network is presented in three levels and classified as superordinate cluster, ordinate cluster and subordinate cluster level. These three levels are the fundamental level of the multi-level interconnected clusters network, which can be described and structured the whole power systems with the flexibility. Moreover, this general definition of those cluster levels leads the buildup cluster network to be a recursive process [101]. The recursive process reduces the complexity of structuring large scale network, because every structuring process is repeated with the same structuring procedure.

To summarize, the bottom-up strategy and the recursive process can be hierarchically applied from the lowest grid level up to the highest grid level in order to structure the clustering network. Consequently, the cluster area can be step wisely established in entire power systems.

3.3 Interconnected Clusters Network

As introduced and emphasized in the previous section that the clustering power systems approach keep the main idea of ENTSO-E interconnected grids. Consequently, it intends to cluster the power systems into several areas, called cluster area, and the bottom-up approach is utilized as the strategy for structuring cluster network. This results the clustering system in the way of multi-level interconnected grids. To figure out the power systems, where the clustering concept is applied, an overview of multi-level interconnected clusters power systems is displayed in Fig. 3.4. It shows the entire of power systems structure from transmission network, distribution network and prosumer unit. Furthermore, this figure is targeted to show that the hierarchical structure of clustering power systems is able to structure from the lowest grid or single unit level toward the highest grid level with consistency and compatibility.

In order to discover how the power systems are clustered, the highest level in Fig. 3.4 is firstly considered. It is obvious in transmission network that the cluster area has already been defined by TSO companies. Furthermore, the interconnections to other areas are clearly presented by the transformer, the connection point to DSO level. Similarly, the cluster areas and the interconnected points in DSO level are commonly described by DSO companies. Conversely, how to cluster the network has to be carefully taken into account in local area, e.g. distribution substation feeder, because the penetrating of DG units in this area is not uniformed. However, clustering area can be considered flexibly. For example, any considered area can be described as the cluster area, if it has as ability to balance the power within area itself, or the cluster area can be selected by the system operator in order to achieve their operation requirements.

In Fig. 3.4, [102], shows further that the DG units are integrated in local grid. With this example, the clustering approach is intended to use in the area, which can produce the energy or control load unit. Regards this outlook, the smart household or prosumer unit can be represented or can be considered as the cluster area. It is important to comment that the clustering power systems are a flexible strategy to support future system-oriented distributed generation network.

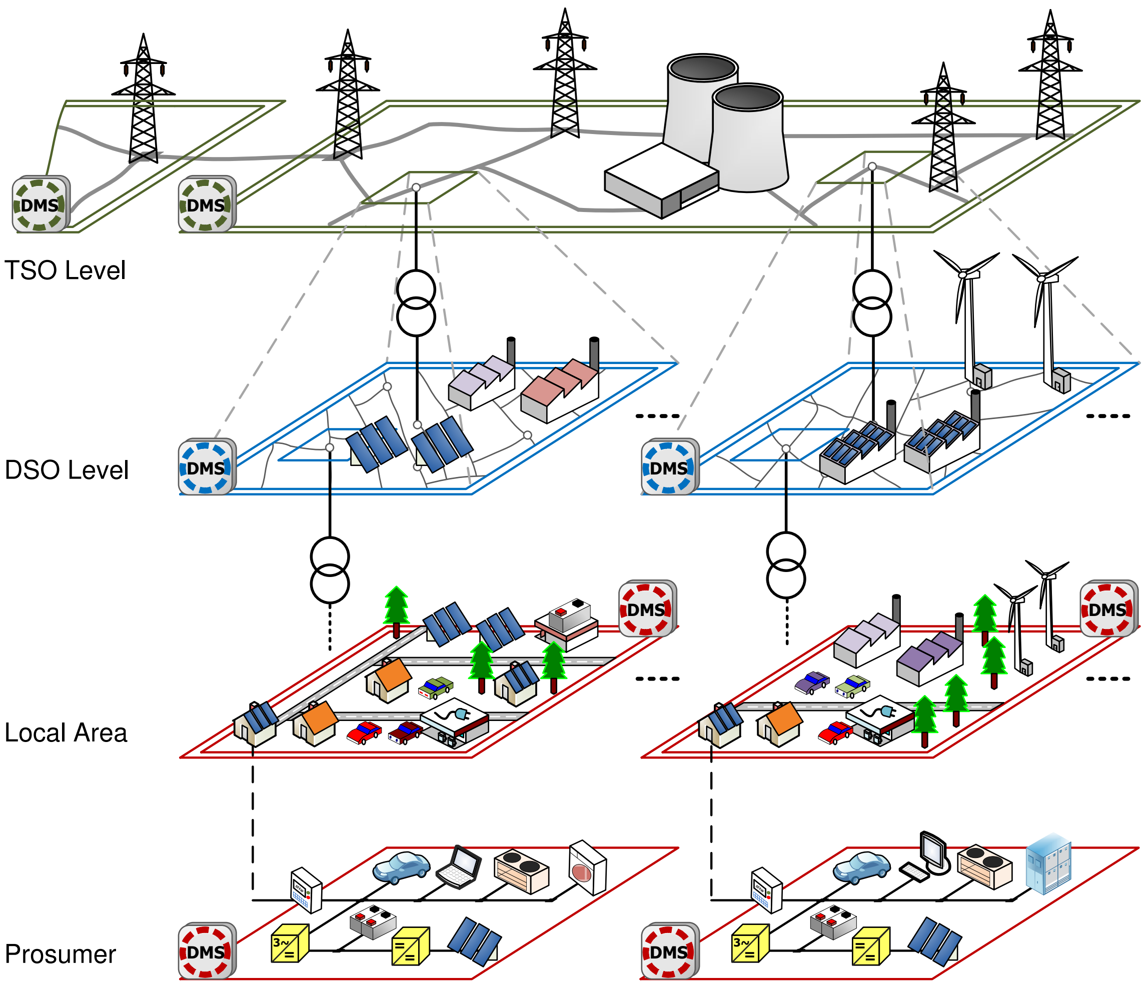


Fig. 3.4: Overview of interconnected clusters network [102]

Additionally, the clustering concept is able to organize and manage the cluster area like TSO functionalities, technical and market operations. In case of interconnected clusters system, the DMS is stated as a controller or an operator in each cluster area. To achieve the DMS functionalities, the cluster management and control functions based on conventional schemes have been continuously developed, e.g., the power flow management in cluster area and between cluster areas. Further information on this issue is described in Chapter 4.

The architecture of clustering power systems results moreover in a great benefit. For instance, the downsized control scheme is the consequent development to follow the evolution of the historical centralized power. Subsequently, it is possible to execute an automated power systems control through a basic conventional power system control approach [26]. Furthermore, clustering's architecture able to reduce the ICT impact [25], since it adds the redundancy into communication platform. Therefore, it is noteworthy to discuss on an impact of clustering power systems strategy; this subject including advantages and disadvantages are debated in the following section.

3.4 Benefits of Clustering Power Systems

As emphasized, the clustering power systems philosophy is developed to establish sustainable energy supply systems, which are the stepwise evolution of conventional grid. To promote this philosophy, its advantages must be discussed and pointed out.

Firstly, an effect of the cluster network structure is considered. As pointed out on previous section that the clustering strategy results in multi-level interconnected clusters network. The benefits of interconnected clusters can be subsequently figured out through the conventional interconnected networks. Traditionally, the transmission interconnected grids are the main electricity network that clearly influences and provides the service process between neighboring countries or cross-border networks. The grid interconnections provide linkages, which allow those countries to transfer and share power generation resources. This advantage of transmission interconnected grids can be transferred and realized in distribution grids by the proposed strategy. Thus, the multi-level interconnected clusters result power systems into uniform structure with consistency and compatibility from the lowest grid level to the highest grid level.

Secondly, since the clustering system delivers a clear network structure, it also leads to the establishment of automated control function in distribution network as the next evolution step. Therefore, the power systems control schemes are discussed. The clustering strategy is aimed to launch automated control functions based on conventional power systems control strategy. This results in downsizing of conventional control schemes. Regards to multi-level interconnected clusters, it also results in multi-level control approach. The main benefit of downsized conventional control is the coexistence between active distribution network and transmission network, since any new novel development must not add the technical complexity or the problems into the existing energy supply system.

To support the future electrical power systems towards to the DG system, it is logical that the complexity is more increased in future grids by integration of automation platform, smart metering, energy trading, etc. Thus, an organization in future system is an essential topic. Fortunately, it can be achieved through multi-level interconnected clusters structure, since this structure clarifies entire power systems with consistency. As regards the well organization, it positively effects on economic process. The multi-level interconnected clusters can construct new economic scale. Sharing energy resources in multi-level interconnected clusters can allow a new construction of electricity market place as well as the liberalization of energy trader. These are the requirements of the future smart market.

Furthermore, the organization can be referred to a management of massive information. Since the intelligent network is applied, the massive information and all measurement data must be processed without avoiding. Due to that, it can be one of the critical issues in the smart power systems. To overcome this issue, a database technique has been globally selected to handle with the massive information. However, without the good coordination, it is impossible to deal with or manage the information. Accordingly, the organization regarding multi-level interconnected clusters are able to enable the guideline for database structure [101]; the information can be thereby stored based on each cluster.

Lastly, the impact of clustering strategy to ICT is discussed. As the ICT systems are the key issue to realize any intelligent applications same as the smart grid, it obviously plays the important role in dynamic power systems control and in many other aspects related to the automation and management of power systems. However, it might cause power systems stability problem due to communication delay [103]. The simplest way but effective concept is to limit or reduce the impact of ICT problem to power systems. The clustering strategy accordingly offers a solution for limiting and reducing the number of constituent units of an automation platform, as the distance between platforms is structurally shortened. The validations of this mentioned strategy are examined and provided in [25]. On the other hand, the multi-level interconnected clusters architecture offers higher reliability in communication system. In case of failures in the communication platforms, a few units are affected, and the remaining systems can continue operation. Conversely, they could automatically return to their previous structure, if the available or suitable platform is recovered from the failures. This means that the clustering strategy adds redundancy and flexibility into communication architecture [104].

In conclusion, the clustering power systems is the flexible philosophy, which is step wisely developed based on the conventional interconnected grids. In order to realize this proposed concept, the automated control functions are introduced and developed based on hierarchical control strategy of conventional system. They are the fundamental functions for enabling advance optimization, management, and economic functions in decentralized system. Their explanations and verifications are given in the next chapter. Finally, this proposed philosophy can be declared as one of the best achievement solutions for the future smart gird applications.

4. Cluster Control Strategy

Recently, the trend of decentralized power systems has been considered as the future of sustainable energy supply systems. The clustering power systems approach is stepwise developed based on the conventional interconnected grids to support and move towards the grid evolution. Regarding the change in future system e.g. penetration of DG units, the distribution system must be participated in power systems control. To overcome and realize the active control in distribution grid, the clustering concept offers the opportunity to establish the cluster control applications, or rather the DMS in each cluster area.

At first, it has to be noted that any new control function for distribution network must not collapse the stability and reliability of the conventional grid. Hence, a recycling hierarchical conventional control strategy is introduced for the distribution control function, since it provides the compatible with the transmission grid control function. The strategy intention is to downsize the conventional control concept. Further information is detailed in the first part of this chapter.

Afterwards, its implementation based on interconnected clusters network is considered. This leads in a change of the conventional control character and supports the expectations of future supply system e.g. reversion of energy flow process. The discussions on the change of control application character including verification simulation case studies are given. As a result, a proposed cluster control application allows opportunities to execute a cluster management and optimization process.

4.1 Recycling of Hierarchical Conventional Control Functions

Dealing with the changes in energy supply system is necessary to understand the background of historical system, hence this section describes the conventional control functions, which are still utilized and operated in transmission system. It is important to keep in mind as general principle for next generation of electrical power systems, since any new development must be coexisted with these existing functions. To figure out the conventional control functions, Fig. 4.1 shows their hierarchical structure regarding ENTSO-E load frequency control policy [40]. These hierarchical control levels consist of the PC at the unit level, the SC at the local level, and the TC at the supervisory level. A brief explanation of conventional control applications and their interactions are given in the following section.

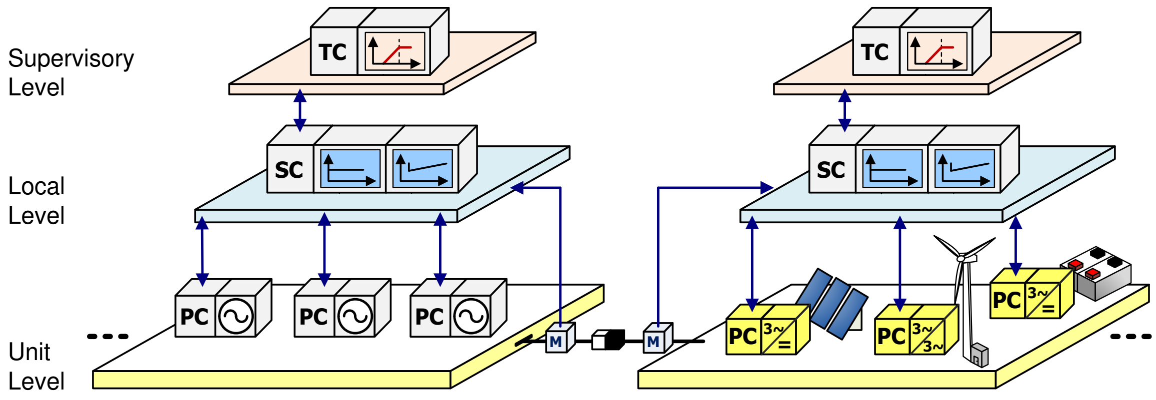


Fig. 4.1: Overview of hierarchical control strategy based TSO [40]

Considering the unit level, it can be noticed that each generating unit is controlled by its own primary controller. The objective of PC is to control the power injection of the generating unit into the grid. The coupling control function or droop can maintain balance between generating units and load consumption. Those processes are functioned by the joint action and the information transfer between all interconnected components within synchronous area. Furthermore, the PC has a responsibility to stabilize the power systems frequency to a stationary value immediately after a disturbance. However, the PC function does not cover the restoration of the system frequency and the power exchanges between interconnected grids to their reference values.

A key responsibility to control and maintain frequency and voltage of control area to the nominal rated values within required time is the SC, which is located at the local level. SC is described as a centralized automatic control function for each control area. It regulates generating units within considered control area. When there is some change in control area e.g. step load, the SC provides a modified set point values to the generating units in order to keep balance condition. Consequently, the power systems state variables are brought back to the nominal value. Moreover, the exchange power between interconnected grids is controlled by this control application as well.

The highest level of hierarchical conventional control is the TC, which located at the supervisory level. The ENTSO-E describes TC as an automatic or manual change in the reference value of generating unit or controllable load in order to guarantee the SC's operation in a right time. A process for overall power system management, forecasting, optimization and etc., are generally performed by TC, which depends on the operation and optimization targets of each transmission system operator.

To describe an interaction between those three control functions, a frequency restoration process is pointed out for an explanation. Different time frames are provided to each control functions, as portrayed in Fig. 4.2, [40]. The fastest activation time is set to PC from 0 to 30s. Shortly before stopping PC operation, the SC is started in parallel with the PC and continued its function. The SC's task is to balance power variation within 15 minutes. Along SC's operational period, PC is still operative, because SC has to adjust the operation point of generation units related to new power balance condition. This means that the PC cannot be deactivated while the SC is operated. Regarding the power variation in the control area, the secondary power reserve must be enough [40]. If it is not sufficient, the TC reserve will take over the secondary power reserve in order to recover the deviation within regulated time. This process is an overlapped process with the working state of SC, as shown in Fig. 4.2. Afterwards, a network optimization process is active e.g. rescheduling of generator or power exchange. This process can be finished within 15 minutes or it may take longer operation time. To conclude these three functions, the PC's and SC's operation is developed to be an automated function. Conversely, the TC can be operated as a manual or automatic function, which is depended on the TSO. Further information related hierarchical conventional control functions can be found in [39], [40], and [46].

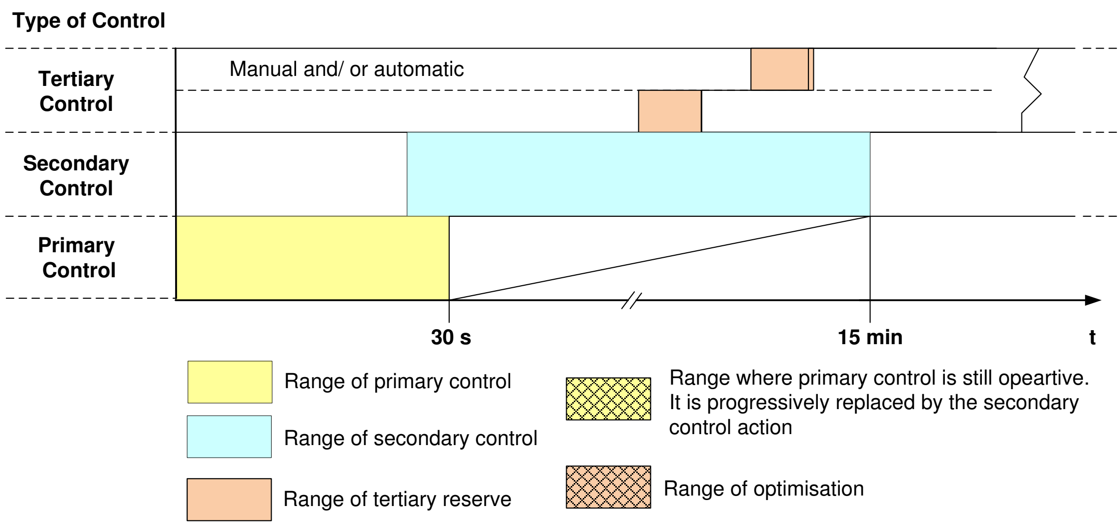


Fig. 4.2: Operation time of hierarchical control strategy [40]

Up to this point, the power systems state variables are controlled based on the hierarchical conventional control functions, which are actively controlled in the transmission level. Since, the DGs based RESs will play an important role in the future as sustainable energy power supply systems, and they will subsequently integrated into existing systems, the improvement of the reliability and quality in entire power supply system must be concerned. Moreover, the new control strategy must not ruin the manner of the conventional strategy. Therefore, a recycling of hierarchical control strategy for future DG systems is investigated as in [105], [106], [107], and [108]. The recycling strategy is developed based on the existing conventional control system strategy. The main function is not only to maintain the voltage and frequency in an acceptable range, but also to share and transfer power between interconnected links. An obvious advantage of implementing this strategy is the compatibility between distributed and conventional electric energy supply systems. In order to figure out the application, a short overview of PC and SC for DG application is given as following.

Firstly, the PC for DG units is taken into account. It is obvious that the interface unit for grid integration is an inverter. Traditionally, the inverter functions like a current source; it feeds all available power of DG unit into grid, named as grid parallel mode. On the other hand, to turn ordinated DG unit to be an active control like centralized power plant, grid forming mode and grid supporting mode is developed [109]. The concepts of both modes are frequency and voltage control to the nominal value, and active power and reactive power control with reference values from dispatcher, respectively. To represent the balancing property between generating units and load consumption, the coupling droop function is also implemented. Since the recycling PC is targeted to implement in distribution network, it should be handled with the character of distribution network. For example, an asymmetrical network condition, to support this character, an asymmetrical control inverter mode is subsequently developed [110], [111], [112], and [113]. Moreover, the most important point is a physical character of the distribution power cable. Commonly, a transmission cable can be described only by the inductance term, but a distribution cable is described by resistance and inductance terms. This fact results in a huge difference. So the decoupling character of droop control function cannot work properly in distribution network. Hence, an adaptive grid impedance droop control is evolved; this results droop control function in flexibility and adaptability regarding grid impedance [47], and [114]. To summarize, the control philosophy of the inverter modular for DG applications is a key to accomplish recycling PC functionality. Obviously, there are other control approaches regarding empowering DG units through inverter units. Selected outstanding approaches can be found in [115], [116], [117], [118], [119], and [120].

Secondly, the SC application for distribution network is considered. When the PC functionalities are enabled and able to deal with distribution network condition, the recycling SC can be subsequently realized as well. The frequency and voltage control schemes of the conventional SC can be directly implemented because the state variables character is identical in entire power systems. In addition, the exchanged active and reactive power between the interconnected grids or mini-grids can be controlled and also managed. A proof of this concept is given in detail in [121], [122], and [123].

Currently, it can be noticed that the new control approaches including conventional control schemes are consequently downsized to distribution network in order to empower the DG units and distribution network. As a result, the power supply systems can be expanded along with reliability improvement. Taking the advantage of downsized control strategy, especially recycling hierarchical control strategy, the realization of clustering power systems approach becomes more obvious, since it is according to the bottom-up approach strategy. Moreover, the cluster network structure, which is resulted in many interconnected cluster areas, can be operated in the same way as ENTSO-E interconnected grids. To figure out and assure the cluster control operation, the description of required control strategy including control schemes are provided in the following section as well as the verification case studies.

4.2 Control Strategy for Clustering Power Systems

Previously, the hierarchical conventional control functions, PC, SC and TC, are introduced. The PC controls the power injection of the generating unit e.g. power plant at its interconnection points into the grid. The energy balancing within the control block or area, the control of the frequency to its nominal value, and exchange power are controlled by the SC. For optimization purpose, the TC is in charge to manage its control area and to provide new balance condition by giving new reference values to SC and PC. Those three control functions are described as the hierarchical conventional control strategy, which is still utilized in the current grids. By the way, these three conventional control functions can be expanded and recycled in order to utilize in the distribution network. As they are applied into low voltage level network, they deliver the compatibility character with the high voltage level; it is the gorgeous advantage of recycling strategy.

Before figuring out the control strategy for clustering power systems, it must be stated that the hierarchical control functions are basically applied for this purpose. Consequently, the three control functions related to cluster control are detailed in this section. To empower the DG units in active control, it is understandably the inverter is used and taken place as an interface unit. It can be implied that the PC is implemented in every inverter unit in order to enable active control function. Nonetheless, the PC can be functioned in difference kind of operation mode, thus, it needs to be clarified.

Considering clustering network structure, as pointed out in Chapter 3 that clustering philosophy results the network structure in multi-level interconnected clusters network, this expresses the future distribution network in the same structure as interconnected transmission grid. The SC functionalities are subsequently taken into account to be an essential control function for balancing power variation within cluster area, and controlling the power exchange between interconnected clusters. However, the SC manner is consequently changed. To clarify the change, this section is contributed for the discussion and validation of a new SC manner. Afterwards, a role of TC oriented distribution management becomes obvious; the realization is concluded in this section as well.

4.2.1 Distribution Generation Unit Control Application

As mentioned, one key of control functions to empower distribution network and to enable the active control ability directly into DG units is the PC, which is able to implement via power electronics unit like inverters. It leads the power generation by DG units to match the requirements of decentralized electric power systems and the control of the power system's state variables, i.e., frequency and voltage.

Traditionally, the DC power from DG units is fed all available power to the grid through the inverter that produces AC output. The power flow is controlled according to the requirement of the energy conversion system (ECS) itself. This mode of operation is called grid parallel mode (GP), which is driven by ECS. On the other hand, to support the requirements of active control, grid forming mode (GF) and grid supporting mode (GS) are evolved [109]. These two modes are basically fed the power into the gird by the requirement of the grid side. The GF mode is developed for generating f and V based on nominal values. The GS mode is designed for P and Q control with external reference values from grid operator. Additionally, each inverter control architecture is developed to support the operation under symmetrical and asymmetrical condition. All inverter control architectures are detailed in [110]. To summarize, the proposed philosophy of inverter feeding modes is shown in Fig. 4.3, [110].

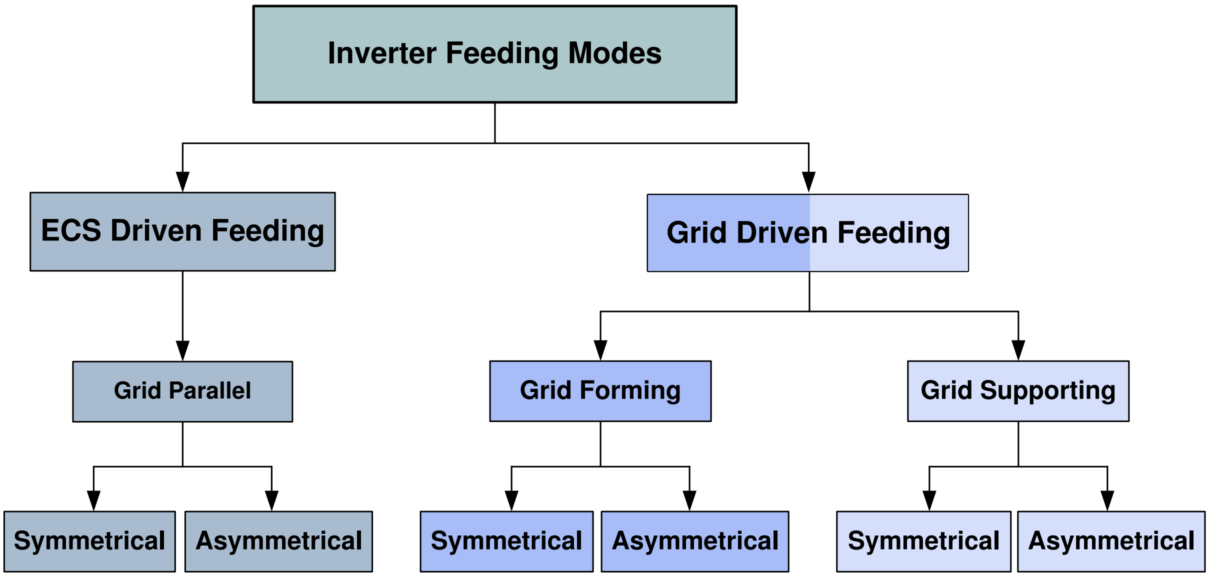


Fig. 4.3: Inverter feeding modes [110]

As a consequence, a grid coupling control function such as droop is considered. The droop control function is defined as PC, which is needed for power sharing purpose when inverters are operated in parallel. Generally, there are two basic coupling modes or droop as following:

- $\Delta f/\Delta P$ and $\Delta V/\Delta Q$ droop for GF mode
- $\Delta P/\Delta f$ and $\Delta Q/\Delta V$ droop for GS mode

The different structures between two coupling modes are related to inverter feeding mode. To further examine, it must have a close look in control schema. All control schemas of inverter with droop coupling can be found on [47] and [110]. Moreover, their application is validated by [105], [106], [107], [112] and [113]. To summarize, through the implementation of the PC, it executes the active control ability. Hence, the inverter is an essential element for DG integration and also the fundamental for cluster control strategy.

4.2.2 Horizontal Cluster Control Application

Currently, each single DG units are active in power control through the implementation of PC via inverter. To move forward, it is time to realize how to control and manage cluster area as well as an interaction between each other. As introduced that clustering approach results the power systems network in interconnected clusters, and the manner of traditional control application is subsequently changed because of the clustering strategy. To figure out this change in control application, the control schemes of the conventional transmission interconnected grids are discussed. Regarding an overview of interconnected grids in Fig. 4.4, it is obvious that one of the most important control functions for interconnected grids is the SC, since it is an automatic control function to regulate the power balance within the certain control area, as well as the stabilization of the system frequency within the synchronous area. All the basic control applications of SC are summarized as following:

- Maintaining and controlling the state variables voltages and frequency to the nominal rated values.
- Controlling the power exchange of interconnected grids.
- Responding the disturbance condition and adjusting the local generating unit power.

Considering a character of this control application, this control can be functioned and cooperated between control areas in the same level. According to this point of view, their interactions are resulted in a horizontal control application: as stated in Fig. 4.4 that the active operation of interconnected power exchanges can be controlled only in the TSO level. A control scheme of horizontal SC is further examined. Since the frequency is the ubiquitous state variable and represents the balancing of active power generation and consumption, it must be mention that the control scheme and investigation in this thesis is concerned only on two parts, i.e., the frequency control part and the related active power control part. A control of reactive power and voltage is not taken into account in this thesis.

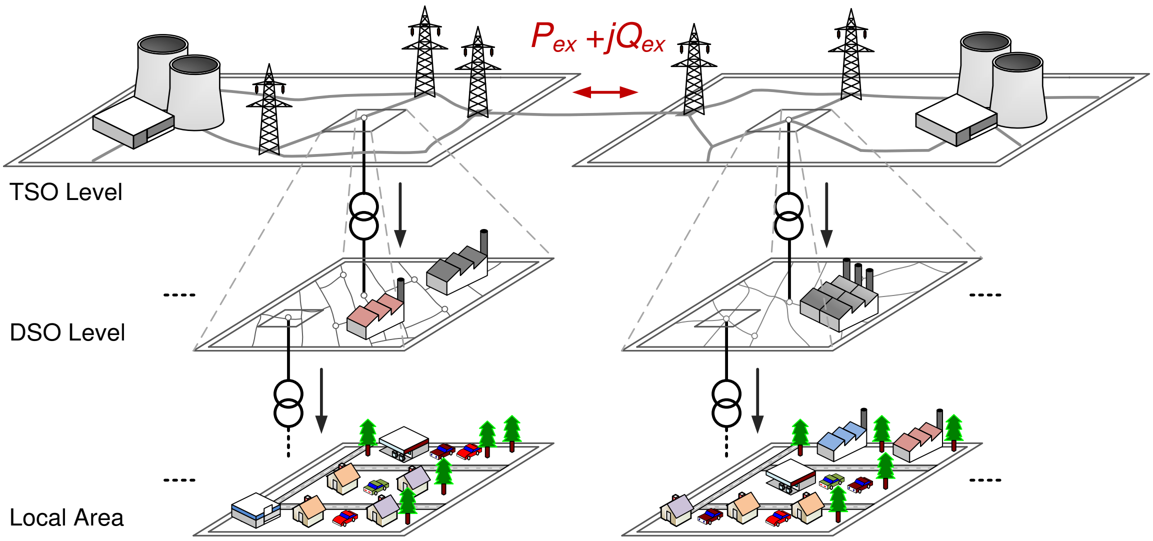


Fig. 4.4: Interaction overview of conventional interconnected grids

To clarify the control application, the frequency and related active power control scheme of the SC for interconnected grid are illustrated in Fig. 4.5, [4]. The frequency control is basically described by the frequency droop control function. It can be observed on both grids, which is written by K_f. Moreover, this frequency droop is also one of control parts for the power transferring between interconnected grids. To accomplish power transferring control process, a typical PI controller is utilized and also standardized by [40]. All operation processes regarding SC's functions based on two interconnected grids can be explained in detail as following:

- Firstly, the power balance condition is taken into account. In this case, there is no power transferring. To achieve this condition, the active power transfer set point is consequently equal to zero ($P_{ref,1} = P_{ref,2} = 0$).
- Secondly, the disturbance condition is considered. For example, a step load is applied to grid1. To support and balance this disturbance in the initial state, the PC in all generator units have to be initially responded in order to maintain system frequency. Afterwards, the SC takes place. The frequency difference (Δf) is controlled by K_f and PI controller in order to bring the system frequency back to the nominal value.
- Additionally, the power flow between interconnected links, which is transferred to support the change during disturbance, is controlled to set condition. In this case, it is controlled to zero, since $P_{ref,1}$ and $P_{ref,2}$ are equal to zero.
- Lastly, the control of exchange power is pointed out. It can be subsequently done by providing the active power transfer set point. A new operating point can be only provided, when both grids are in steady state condition. This action can be referred to optimization process of TC.

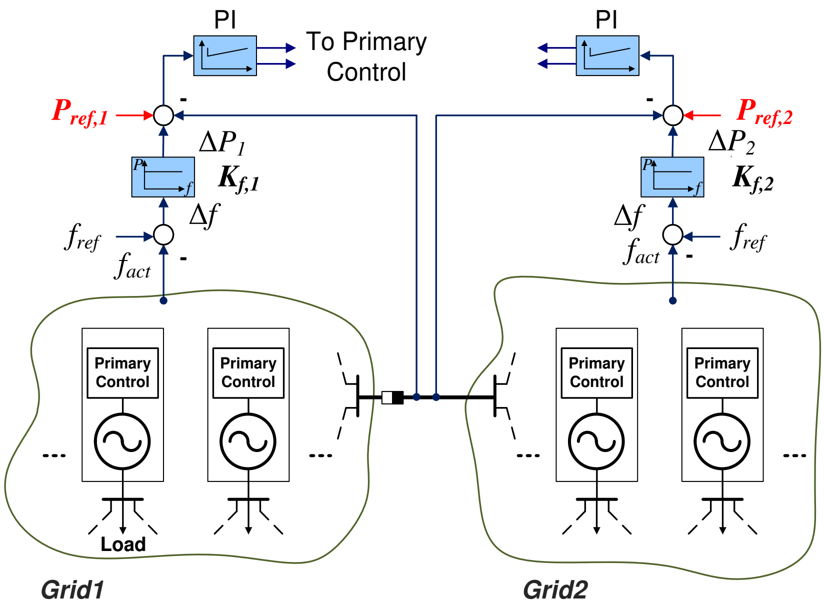


Fig. 4.5: Control scheme of conventional interconnected grids [4]

To conclude, this horizontal control application or SC is described based on TSO level. Regarding the control features, it is carried out for assuring the power systems frequency and managing the exchanged active power between interconnected grids purpose. As emphasized, the conventional control scheme has to be extended to distribution level through recycling hierarchical conventional strategy; consequently, its implementation in distribution network is further examined.

Since the clustering power systems approach describes and structures the power systems network in the art of interconnected clusters, the SC is subsequently concerned as the essential control application of each cluster area in order to enable the active control function in distribution network. This results in the downsizing of SC [106] - [108]. To figure out the control scheme, three interconnected clusters systems including control scheme are portrayed in Fig. 4.6. The three-cluster system is intended to show that the implementation of downsizing of SC is able to function in distribution network.

Before starting the discussion on horizontal control scheme in distribution network, it must be stated that the PC is implemented in all inverter units. Fig. 4.6, [108], shows that the control scheme is taken from the conventional interconnected TSO grids. Hence, the frequency control part contains the K_f on each cluster. Absolutely, the frequency control function is further adapted and utilized for controlling the power transferring between interconnected clusters, which are accomplished through PI controller. This leads the cluster operation in the same way as conventional grids.

Typically at normal state, each cluster is balanced the power based on area itself; no exchanged power in this condition. Consequently, P_{ref} is set to zero. If any disturbance, failure or load change occurs in one cluster area, it will be held up by producing more power to carry the faulty area. For example, a fault occurs on the cluster1 (e.g. one generating unit is collapsing), then the additional power flows from cluster2 and cluster3 to cluster1 in order to stabilize the system as defined by the grid code regulation. In this state, it is a responsibility of PC in all generation units. It means that the transferred power between clusters is increased; meanwhile the system frequency drops.

Afterwards, the frequency droop control of the SC comes up to overcome this influence. An offset value is signaled to the PC, in order to adjust the gap of the frequency deviation and bring it back to nominal value. Additionally, the transferred power between interconnected clusters can be defined by P_{ref} on each cluster controller. This can be done after each cluster is back to balance condition, regarding the SC regulation.

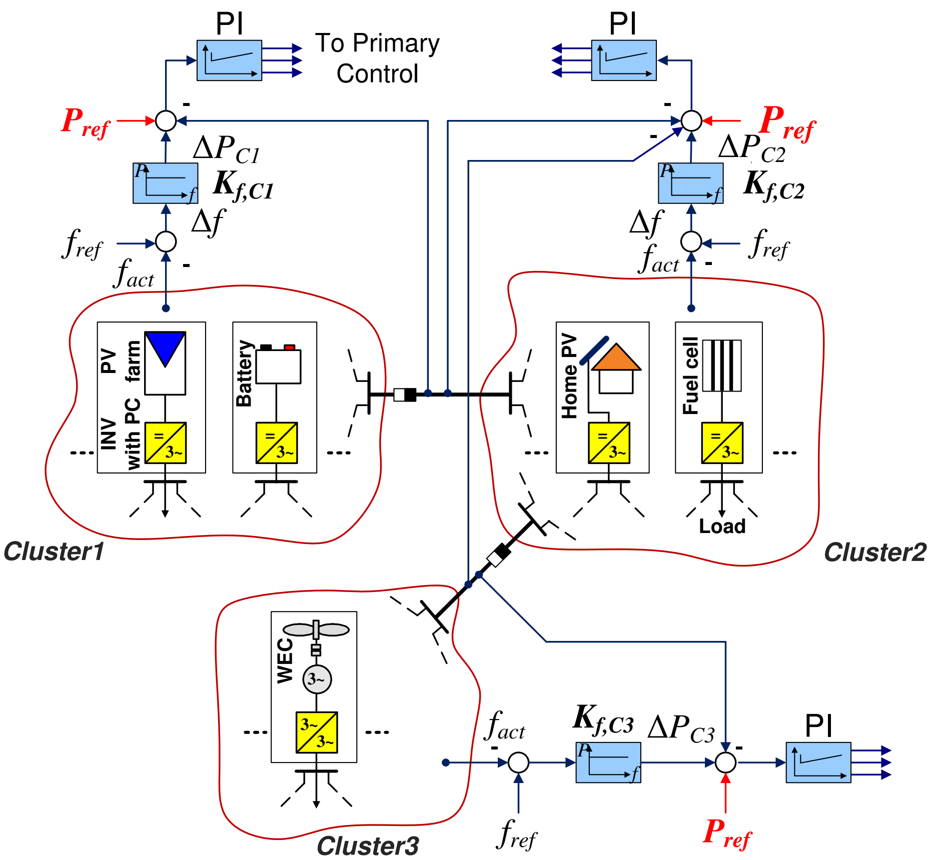


Fig. 4.6: Horizontal control scheme in distribution network [108]

Based on the discussion of three interconnected clusters operation, the behavior is obviously represented the operation of conventional interconnected grids. Therefore, the horizontal control application or SC function can be downed scale to distribution system through the clustering power systems concept. According to this fact, it can be implied that the energy flow between interconnected clusters in distribution level or prosumer unit can be controlled and managed. Hence, an opportunity is available to reverse energy flow process from low voltage level to high voltage level, which is expected in future power supply systems. This expectation can be successes through a vertical control application, which is proposed and elucidated in the next section.

4.2.3 Vertical Cluster Control Application

According to previous discussion, the frequency control and the power transfer between interconnected clusters on the same cluster level are clarified. Nevertheless, the clustering power systems approach results the network in multi-level interconnected clusters system, the interconnection between superordinate, ordinate and subordinate cluster, as mentioned in Chapter3. Hence, the interaction between clusters in different cluster level is described by a vertical process. Subsequently, the power transferring process to another cluster level is developed and introduced by the vertical SC application.

Initially, the vertical SC application idea is proposed and examined based on mathematics description, which a former name is called by multi-level SC application [25]. Since this concept delivers a great benefit in decentralized power systems automation and control, therefore, it is further developed and presented with dynamic grid model in [124], and [125]. In order to emphasize and forward this strategy, the control scheme and functionalities of vertical control approach are clarified. Based on single cluster level in Fig. 4.6, cluster4 is now added into the system and described as the superordinate cluster level as illustrated in Fig. 4.7, [125]. This cluster4 is considered as different voltage level network. Likewise, the cluster control function based on SC is applied into cluster4's controller. Clearly, the same control functionalities are repeated once again: balancing power within cluster area, controlling of interconnected clusters power transferring, and maintaining system frequency. According to cluster1, cluster2 and cluster3, these three clusters are currently considered as generation or load unit based on the cluster4 point of view. Regards this aspect, the subordinate cluster is concerned as active element for ordinate cluster level. Thus, it can be implied that the power exchange can be managed and transferred to different cluster level, which called the vertical application.

Having a look on the vertical control scheme, which is described by cluster4 in this case, the frequency droop control is implemented in cluster controller to stabilize the systems frequency. The PI controller is understandably implemented in order to control the power transferring between interconnected clusters. The offset value (P_{offset}) in this case is signaled not only to the PC but also to the SC of subordinate cluster. The offset value from cluster4 or superordinate cluster P_{offset} is the key element of the vertical control application. For example, P_{offset} is applied in the SC of cluster1, cluster2 and cluster3, is the result value from the cluster4 controller. Moreover, the same value is also applied to PC, which is considered as the element of cluster4, e.g., generator as noticed in Fig. 4.7. Similarly, the proposed control scheme is able to apply to the higher cluster level.

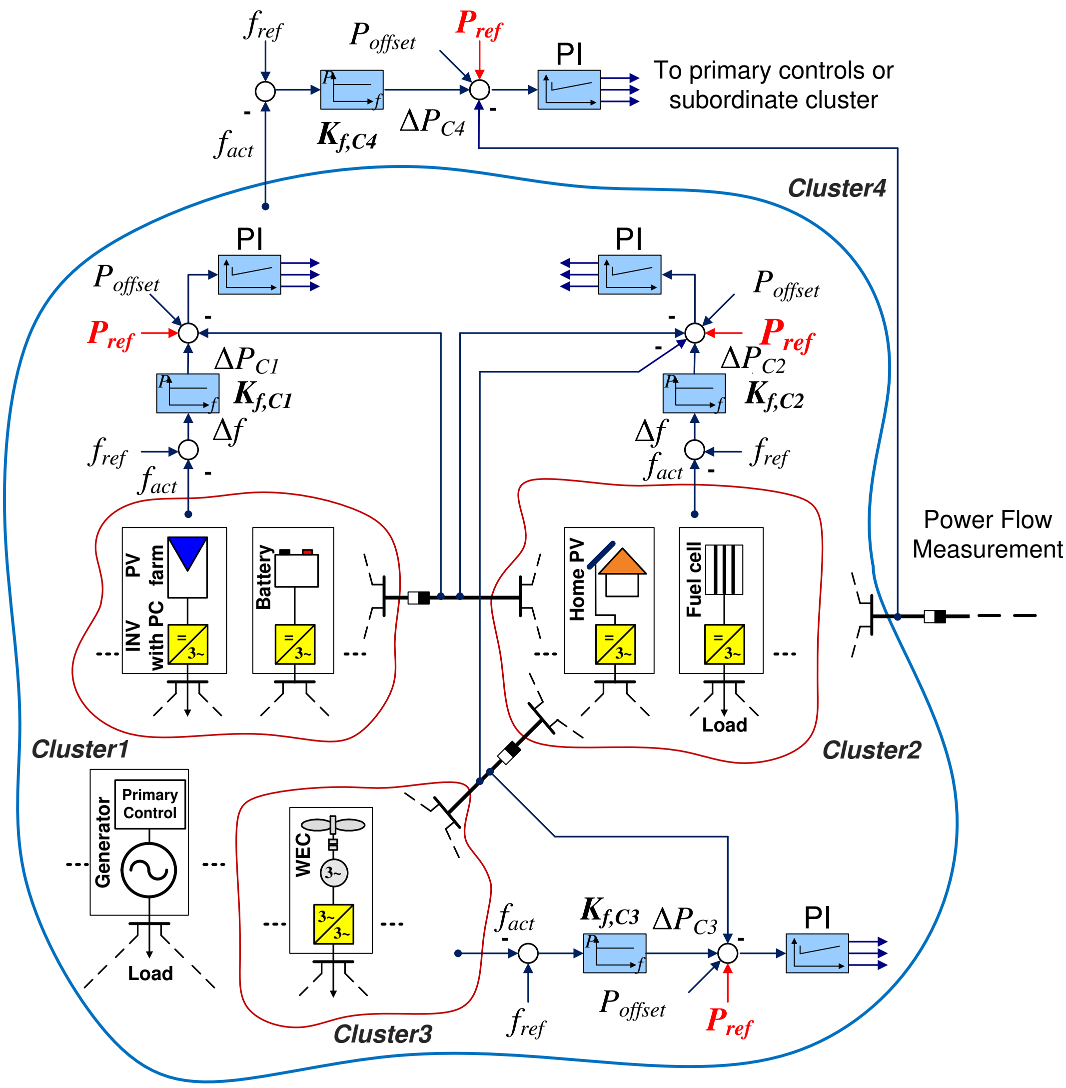


Fig. 4.7: Vertical and horizontal control scheme of interconnected clusters [125]

Regarding the discussion, the implementation of multi-level cluster controller results the operation and the interaction in vertical way. As emphasized, the important rule for the creation of advanced grid control functionalities is to ensure their compliance to the existing conventional grid control strategies and structures. Therefore, the generator unit, as stated in cluster4, is an index to illustrate that the recycling hierarchical control strategy can be coexisted with the conventional system.

In summarization, the implementation of vertical and horizontal cluster control application in distribution network gives the opportunity to change the ordinate passive distribution network to be an active network. Consequently, the active distribution network can participate in the whole power system control. As a result, the entire power system is empowered and able to interact to each other; from prosumer level up to TSO level as depicted in Fig. 4.8, an overview of multi-level interconnected clusters system with cluster controller.

Moreover, applying the proposed control strategy based on clustering network structure can assure that even in case of fatal blackouts of the entire cluster, as the cluster area is still able to operate independently. If the surrounding cluster completely fails, the independent cluster can still locally supply direct to the related loads with their capabilities. Furthermore, it can support a re-establishment of the system after recovering blackouts by the cluster controller. In order to verify the proposed vertical and horizontal control application, the case studies are employed in the next section.

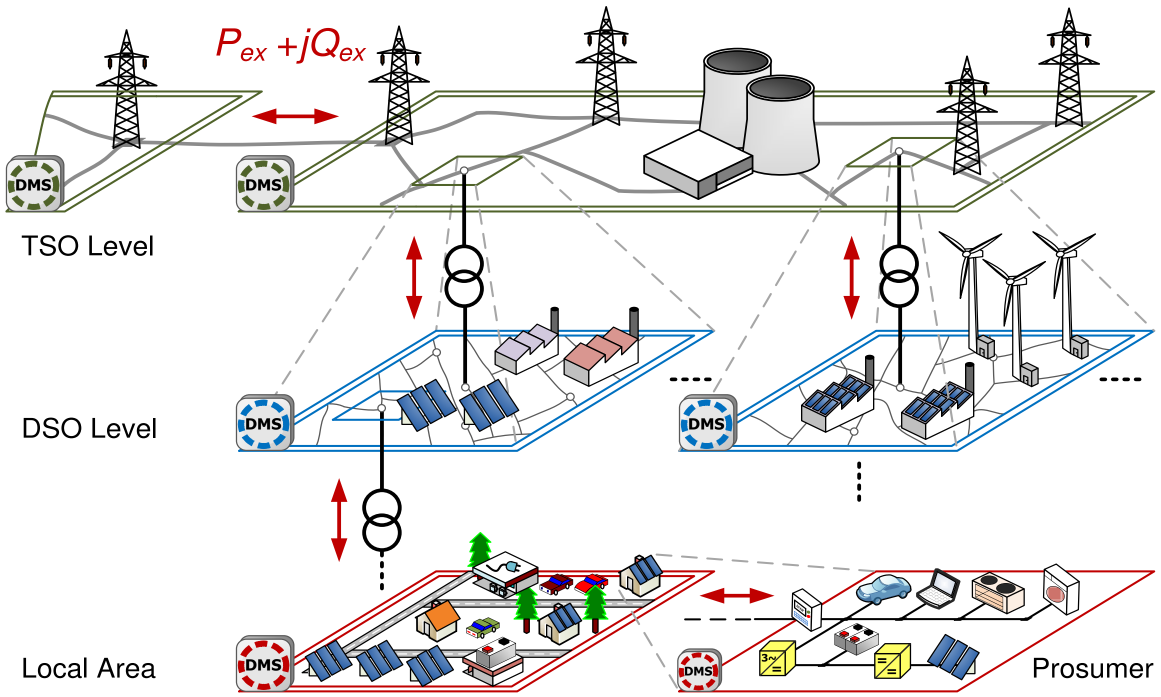


Fig. 4.8: Empowering interconnected clusters system with cluster controller

4.3 Verification of Cluster Control Applications

Before starting verification by case studies, it must be emphasized that the proposed vertical and horizontal cluster control application is developed based on clustering power systems approach, which is aimed to operate based on each cluster area. Hence, it is necessary to have a decoupling simulation platform for clustering network in order to achieve a reliable result. Consequently, a dynamic Root Mean Square (RMS) synchronous generator model is initially taken into account. This dynamic-RMS model can be compared with the full scale dynamic fourth order synchronous generator model, the comparative results of the terminal voltage between the RMS model and full scale synchronous generator is a proof of this simulation platform. Regarding the simulation platform, the RMS model is combined with a mathematical grid model or a bus admittance matrix in order to perform load flow analysis. Further information of this load flow simulation platform can be found in [126], [127], [128], and [129]. It must be noted that this platform cannot describe the transient behavior of grid because the grid model is defined by static mathematical model. However, the proposed cluster control applications can be tested because the action period of SC is not executed during transient period. The basic description of simulation platform is given in section 4.3.1.

To emulate the cluster operation process, the dynamic-RMS load flow simulation platform is further developed based on hybrid calculation approach, because it offers an opportunity to decouple the load flow analysis. As a direct result, the dynamic-RMS load flow simulation platform can perform in a decoupling way. The validation of the decoupling load flow simulation platform is detailed in [130], and [131]. To clarify and figure out an advantage of hybrid calculation technique, its derivation as well as the application for the cluster analysis strategy is further detailed in Chapter5.

In order to validate the proposed vertical and horizontal cluster control applications, this section illustrates simulation case studies and discussion. There are two case studies, i.e., the verification of horizontal cluster control application and combination of vertical and horizontal cluster control applications. Brief explanations of both case studies are explicated below, respectively.

In the first case study, three interconnected cluster systems, which all are described in the same cluster level, are focused. In order to examine cluster power exchange control function, two interconnected links are defined: cluster1-cluster3 and cluster2-cluster3. Additionally, cluster4 is added into the examined system as the superordinate cluster of those three clusters; therefore, the controller of cluster4 (DMS4) is only in charge for power balancing purpose. This means that the first case study validates the horizontal cluster control application based on active power and frequency control. Furthermore, the management concept through superordinate cluster is also demonstrated.

The second case study, two cluster levels with five interconnected cluster systems is introduced. The examined cluster system is basically based on previous network structure. To ensure the vertical control application, a cluster5 is added into the tested system and declared as superordinate cluster level. Since the superordinate cluster5 is connected with ordinate cluster3, this is an indication to illustrate that the vertical control concept gives the opportunity to reverse power flow process. Obviously, the combination between horizontal and vertical control scheme and the discussion based on the reversion of power flow process and frequency stability are the main point of this study.

The cluster controller of all case studies is indicated by DMS. Regarding the multi-level control structure, which is introduced in this section, it can be implied the SC scheme is currently implemented in DMS control application. The proposed control strategy is use to handle with the distribution network. The generation types, the rated power, the nature of the electrical load and the network element are therefore described according to LV system. In addition, the dynamic synchronous generator RMS model [126] and the dynamic inverter RMS model [132] is considered as a generating unit. The studies are concerned on the relative active power generating, the exchange active power between interconnected clusters and the power systems frequency. Lastly, it must be noted that all case studies are simulated by MATLAB/Simulink version R2008a.

4.3.1 Simulation Platform - dynamic RMS Model

As declared that the dynamic-RMS model is selected as the simulation platform for validation of the proposed cluster control strategy, thus, it is noteworthy to have further look on detail. Originally, the dynamic-RMS model is evolved to reduce a complexity in an analysis of the complete power system behavior because the use of full scale dynamic simulation to observe the grid frequency and voltage response leads to a considerable computational problem. Regarding a generation unit, a synchronous generator and inverter are taken into account. The synchronous generator is selected in order to represent a conventional power source. On the other hand, the inverter unit stands for a concept of DG unit. Hence, it can be implied that the dynamic-RMS model is also aimed to show the coexistence between a conventional system and a future system like DG.

To simplify, an advanced modeling of electrical power distribution systems using dynamic-RMS method is initially proposed [133]. Fig. 4.9 depicts a general idea of a simulation platform. Noticeably, the model is separated into two parts, a dynamic part and a RMS part. The dynamic part describes the frequency and voltage behavior of each generation unit type.

On the other hand, the RMS part corresponds to a terminal bus voltage of each generating unit or load. This is a linkage between dynamic part and RMS part. Therefore, the voltage distribution and the load flow are able to simulate under steady state conditions. Moreover, the proposed dynamic-RMS method also offers several advantages such as reduction of computing time leading to fast simulation of complex power systems while achieving almost similar results compared to a full scale dynamic model.

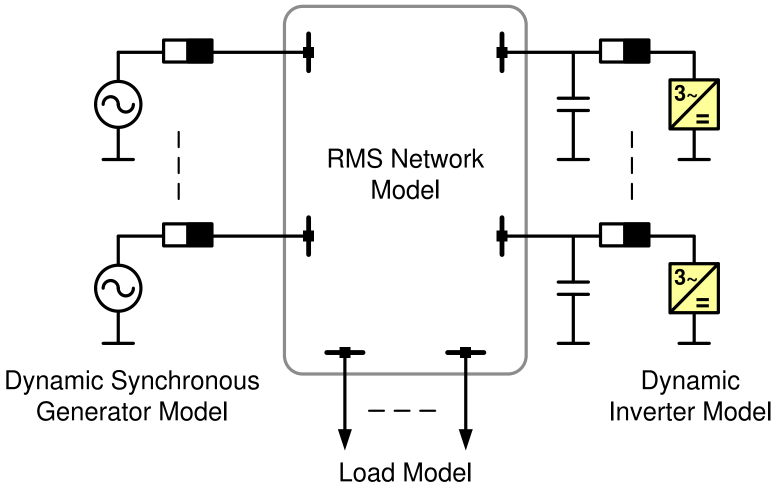


Fig. 4.9: A general idea of dynamic-RMS model [133]

To elucidate both parts, the subsections are structured in the following manner: First, the dynamic model as well as its control functions of the frequency generation part is described. Afterwards, the dynamic voltage generation model is defined. Next, a coupling method between frequency part and voltage part is described. Finally, the mathematical description of the electrical grid or RMS part is introduced.

4.3.1.1 Dynamic model of frequency generation part

Describing full scale dynamic frequency behavior of any generation unit needs a lot of information in order to obtain a reliable model. For example, a mechanical informations, inertia, friction model, etc. are required for modelling synchronous generator. In case of inverter unit, a phase lock loop (PLL) model is essential for measuring the frequency output. To reduce the complexity and define it in general way, a first order system (PT1) is subsequently used for those purposes. By tuning the PT1 plant and comparing output with the reference model, the dynamic frequency behavior can be easily accomplished. Fig. 4.10 illustrates a frequency generation unit with frequency droop coupling function. The frequency droop control function is the classical control of the conventional system. The implementation of droop control function in inverter unit has been discussed in the previous section. The difference between the reference active powers (P_{ref}) and the generating active powers (P_{act}) is the effect of the system frequency over droop function (K_ω). In the control loop, PI controller is applied for frequency control. Moreover in this control loop, the coupling frequency ($\omega_{coupling}$) is one of important parameters. It is necessary to couple all frequency of the generation units in order to generate one systems frequency; this will be explained in detail in frequency equalizer section.

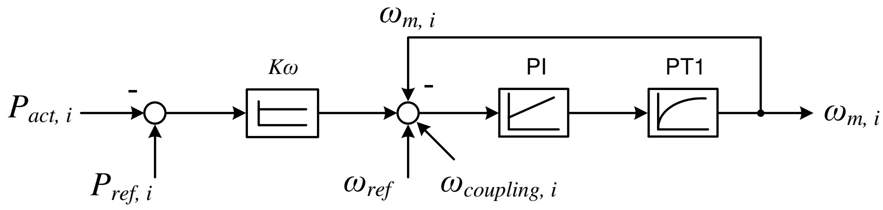


Fig. 4.10: Frequency generation model with frequency droop control function

4.3.1.2 Dynamic model of voltage generation part

Similarly, the dynamic behavior of the generating voltage or terminal voltage is able to be described by PT1 plant in the same way as the frequency part. A model of voltage generation is consequently introduced as shown in Fig. 4.11. Clearly, the voltage control droop function (K_U) is implemented in the model, which controls reactive power by using the difference between reference reactive powers (Q_{ref}) and the generating reactive powers (Q_{act}).

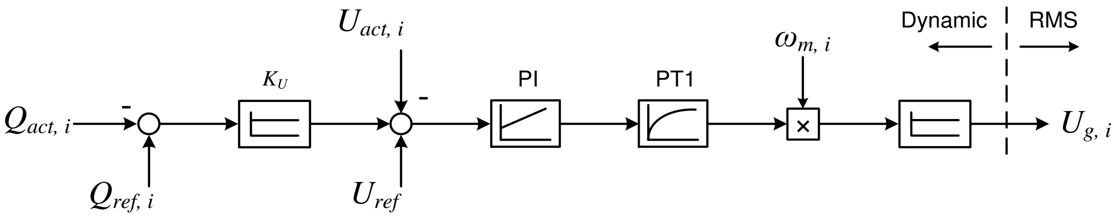


Fig. 4.11: Voltage generation model with voltage droop control function

To complete the dynamic model, the frequency and voltage dynamic models have to couple in order to reflect the behavior of each other. To do that, the generating frequency character is added into the voltage model by multiplying generating frequency ($\omega_{m,i}$), and subsequently dividing by its amplitude to keep the concomitant voltage.

Finally, to prove the proposed modeling technique, a full scale dynamic synchronous generator model from SimPowerSystems, MATLAB is considered as a reference as well as the inverter model in [112]. The comparison results of system frequency and terminal voltage of each model are given in [126] and [132], respectively,

4.3.1.3 Frequency Equalizer Model

In fact, the systems frequency is unique in power network. However, the developed frequency model is generating the individual frequency of each unit. Due to this reason, the frequency equalizer function is introduced in order to generate the system frequency. This function is working in order to determine the difference between unit frequency and the average frequency of all units, called coupling frequency ($\omega_{coupling}$), [133]. The calculation of coupling frequency can be described in matrix form as shown in Eq. (4.1). This coupling frequency will be added into the frequency model as an offset to adjust the system frequency, as noticed in Fig. 4.10.

$$\begin{bmatrix} \omega_{Coupling\ 1} \\ \omega_{Coupling\ 2} \\ \omega_{Coupling\ 3} \\ \vdots \\ \omega_{Coupling\ n} \end{bmatrix} = diag\left[K_i\right] \times \begin{bmatrix} n-1 & -1 & -1 & \cdots & -1 \\ -1 & n-1 & -1 & \cdots & -1 \\ -1 & -1 & n-1 & \vdots & -1 \\ \vdots & \vdots & \cdots & \ddots & -1 \\ -1 & -1 & -1 & -1 & n-1 \end{bmatrix} \times \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \vdots \\ \omega_n \end{bmatrix} \tag{4.1}$$

where n is the number of the inverter, ω_i (i=1,2,3…,n) is the frequency of each generating unit and gain K_i is an average factor.

4.3.1.4 RMS Power Systems Network Model

According to the general idea of dynamic-RMS model in Fig. 4.9, the RMS part is also related to power network model. In general, a bus admittance matrix is normally considered for describing the system structure. A single line diagram based on the π- equivalent model is used to represent a mathematical model, shown in Eq. (4.2).

$$\begin{bmatrix} \underline{U}_1 \\ \underline{U}_2 \\ \vdots \\ \underline{U}_n \end{bmatrix} = \begin{bmatrix} \underline{Y}_{11} & \underline{Y}_{12} & \cdots & \underline{Y}_{1n} \\ \underline{Y}_{21} & \underline{Y}_{22} & \cdots & \underline{Y}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \underline{Y}_{n1} & \underline{Y}_{n2} & \cdots & \underline{Y}_{nn} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \underline{I}_1 \\ \underline{I}_2 \\ \vdots \\ \underline{I}_n \end{bmatrix} \tag{4.2}$$

Where n is the number of buses in the power system, $\underline{U}_i$ (i=1,2,3,…,n) is the complex vector of terminal voltages. $\underline{I}_i$ (i=1,2,3,…,n) is the complex vector of bus currents. $\underline{Y}_{ii}$ (i=1,2,3,…,n) is the self-admittance of bus i, which is given at the diagonal elements. $\underline{Y}_{ik}$ (i,k=1,2,3,…,n) is the mutual admittance between buses i and k.

To combine dynamic part and RMS part, by means of completing simulation platform, a classical power systems analysis by injection current method is taken into account. This method can also utilize with intelligent components, i.e. inverter, by considering those components as a current source. The concept of this method is to build up the current summation of each bus and define the current direction by mathematic symbol. The positive current is the current flowing into the bus, whereas, the negative current is the current flowing out of the bus. In order to figure out an implementation of current injection method, the inverter model is used as an example. The introduced inverter model in the previous section is unfortunately working as a voltage source. Due to this reason, the generated inverter voltage ($U_{g,i}$) has to be converted into current form ($I_{g,i}$). The equivalent circuit of inverter model can be described as portrayed in Fig. 4.12. The information about current converting of any generating voltage source is further described in [133].

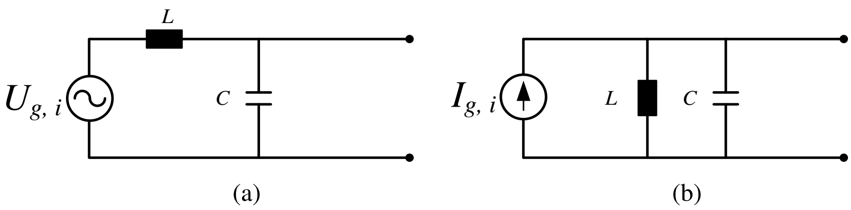


Fig. 4.12: Equivalent circuit of inverter model

Regarding a load model, it is also describe in the part of RMS. The active power and reactive power load are only concerned. Obviously, the load model must be defined in current form, which can accomplish through Eq. (4.3). It can be seen that the complex voltage at load bus plays an important role in reflecting the dynamic of power grid in load model.

$$\underline{I}_i = \left(\frac{P_i + jQ_i}{\underline{U}_i} \right)^* \tag{4.3}$$

To conclude, the dynamic-RMS model minimizes some complexity of generating unit function, this results in the fast simulation while achieving the same behavior of the full function model. Additionally, it is further developed based on a hybrid calculation approach to structure the interconnected clusters network character, which the hybrid method is detailed in chapter5. Hence, the proposed cluster control strategy is examined and validated based on dynamic-RMS model.

4.3.2 Case Study1 - Horizontal Control Application

To verify the horizontal cluster control application in distribution network, a low voltage system, which is structured based on multi-level cluster approach, is developed and examined. However, this case is focused only on the horizontal control- and the management application, thus cluster1, cluster2 and cluster3 are considered as in the same cluster level. As portrayed in Fig. 4.13, there are three interconnected clusters on the same level, declared as ordinate cluster level. Three clusters are defined with different generating units. Cluster1 and cluster3 are taken into account as conventional system, therefore, the synchronous generator model [126] are utilized. On the other hand, cluster2 is implemented with inverter model [132]. This can be implied that the proposed control strategy is able to use with both conventional generating unit and DG unit.

In order to complete the power balancing application, the superordinate cluster is required. The cluster4 is described as superordinate level; three ordinate clusters are considered as generating or load units. Regarding control application, DMSs are stated as cluster controller. Consequently, the control scheme of examined interconnected cluster can be referred to Fig. 4.6, the horizontal control application.

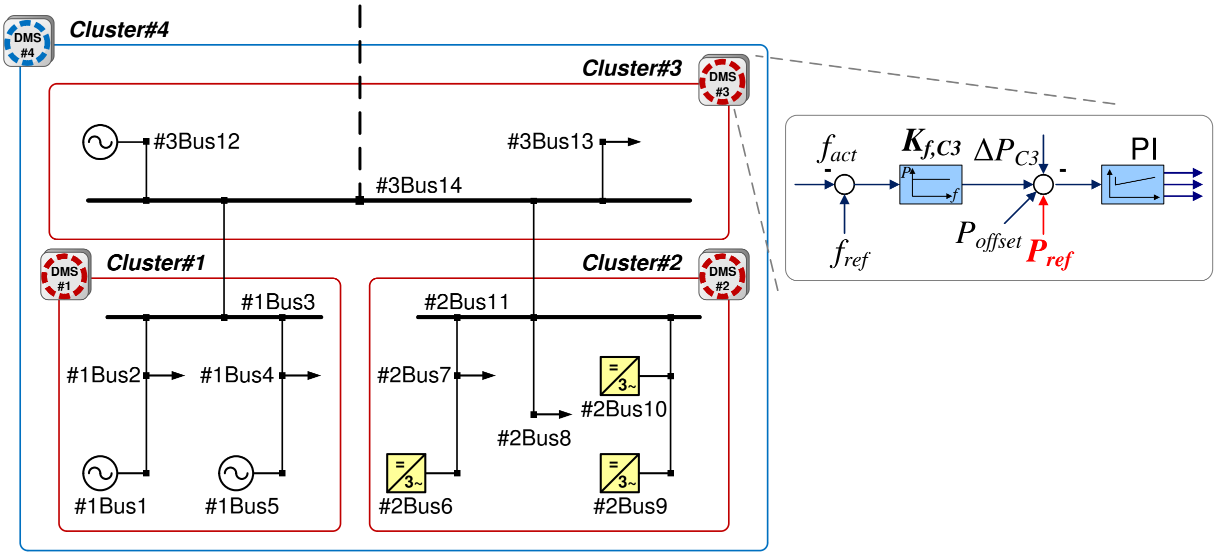


Fig. 4.13: Examined interconnected cluster systems

As mentioned that the proposed control application is focused on relative power generating, exchange power between interconnected clusters and frequency stability. Next, the discussions on those issues are stated in following parts. It is noteworthy to mention that the tested system is considered as a symmetrical system. The simulation is done on MATLAB/Simulink based on hybrid decoupling power flow analysis platform.

The parameters for the examined interconnected cluster systems are considered based on a low voltage network description, where rated voltage is 400 $V_{L\text{-}L}$; and rated frequency is 50 Hz. The reference values of each generator, inverter and applied load are detailed and illustrated in Table 4.1. Each bus is connected with 100m NAYY 4x50 SE cables; R_l = 0.772 Ω/km and X_l =0.083 Ω/km.

Table 4.1: Reference value of generator, inverter and load

		P_{ref} [pu.]			P_{load} [pu.]
Cluster1	Gen1	1.00		Load2	1.00
	Gen5	1.00		Load4	1.00
Cluster2	INV6	0.666		Load7	1.00
	INV9	0.666		Load8	1.00
	INV10	0.666			
Cluster3	Gen12	1.00		Load13	1.00

In order to analyze and demonstrate the characteristic of horizontal control application, the simulation events are given and divided into three parts. Firstly, at 100s, the 0.25 pu. step load is applied to load13.

In this case, the power balance functionality as well as the frequency recovering function of each cluster is tested. Secondly, the power flow management function is examined at 300s. The power exchange reference values are defined and provided to all three clusters in the event. Lastly, the flexibility and the adaptability of control function are tested. Hence, DMS2 is set to be out of order; DMS3 has to be subsequently in charge of this change and set new reference point to all generating units in cluster2. All simulation events are detailed in Table 4.2.

Table 4.2: Overview of simulation events

Time [s]	Simulation events
100	Applying 0.25 pu. active power step load to cluster3 Load13
300	DMS4 has managed applied power of the subordinated clusters as following: • Cluster1 applying 0.083pu. to cluster3 • Cluster2 applying 0.042pu. to cluster3
500	DMS4 has managed DMS3 in order to take place on cluster2, since DMS2 is out of order.

A. Discussion on power generation and power exchange between cluster systems

The discussion on this section is focused on power generation of each generating unit and active power exchanges between cluster systems. According to the examined cluster system, there are two interconnected positions, which are located in the ordinate level. They are interconnected between cluster1-cluster3 and cluster2-cluster3. Firstly, the results of all generating units are discussed in order to illustrate the unit level characteristics, as shown in Fig. 4.14, separated by cluster area. Secondly, the clarification of horizontal cluster control approach is taken into account; this can be explained through the power exchange between interconnected clusters.

Their simulation results are presented in Fig. 4.15. Lastly, the zoom of power exchange between clusters during first simulation event is portrayed in Fig. 4.16. The discussion of each simulated event is listed as following:

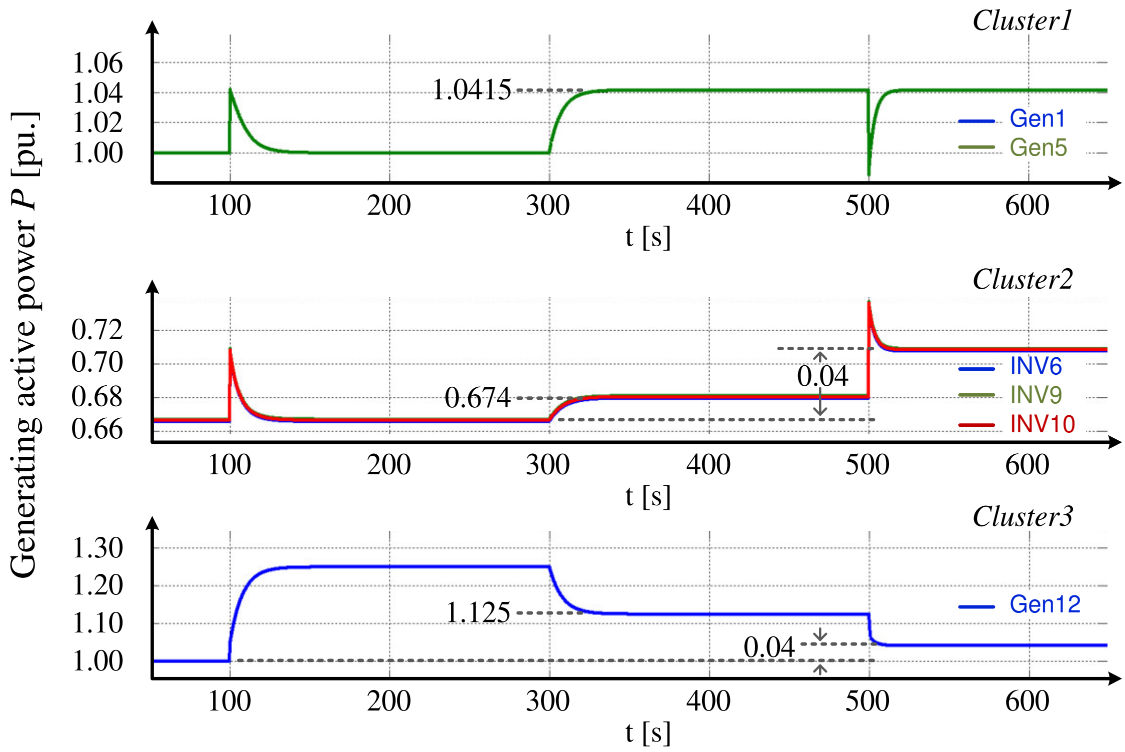


Fig. 4.14: Active power of each generating unit

- After every cluster is in balance condition, the first simulation event is executed at 100s, 0.25 pu. step load is applied at cluster3, load13. As regards the grid code regulation, at the beginning of this period, all generating units have to support this load change. As shown in Fig. 4.14, all generating units on cluster1, cluster2 and cluster3 increase their generated power to support this load change. Afterwards, they decrease the power and back to the nominal state when the generating unit on cluster3, Gen15, can support this change. Regards the power exchange between clusters, Fig. 4.15 also shows that cluster control can maintain the cluster balancing.
- At 300s, DMS4 manages a new active power reference point to each cluster. The cluster1 is required to support cluster3 by transferring 0.083 pu. of active power. Similarly, cluster2 is also required to send 0.042 pu. of active power to cluster3. The exchange power simulation results show a correct condition. Moreover, it is obvious that the generating unit on cluster3, Gen12, decrease the power generation from 1.25 pu. to 1.125pu.

- At 500s, DMS3 has to handle cluster2, since DMS2 is out of order. This means that all generating units on cluster2 have to be adapted and changed their active power generation. If the automated sharing function or droop work properly, the generating units have to result the same relative active power generation. This can be noticed in Fig. 4.14, INV6, INV9, INV10 and Gen12 are resulted the same relative power generation, 0.04 pu., from their initial reference value.

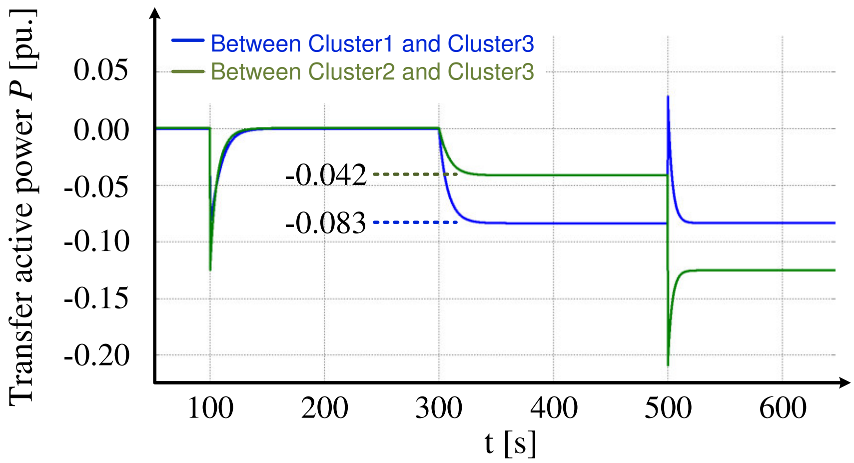


Fig. 4.15: Active power exchange between clusters system

In order to describe the characteristic of PC, the step load is a good case to examine. Thus, the zoom on active power exchange between clusters during the first simulation event is show in Fig. 4.16. As mentioned that when load is changed all generating units have to support his change with the same amount. This can be observed in Fig. 4.16; cluster1 transfers 0.083 pu. active power to cluster3 and cluster 2 transfers 0.125 pu. to cluster3. Since cluster1 has two generating units and cluster2 have three generating units, it can be calculated that each unit increase the generated active power by 0.041 pu. to support the load change. It is noteworthy to mention that dynamic behavior of the transfer power between cluster2 and cluster3 is faster than the other because the inverter responds faster than synchronous generator.

After discussion about power generation and power exchange between clusters, the simulation results validate the power control scheme of horizontal application. Moreover, the relative power sharing on unit level is also worked properly

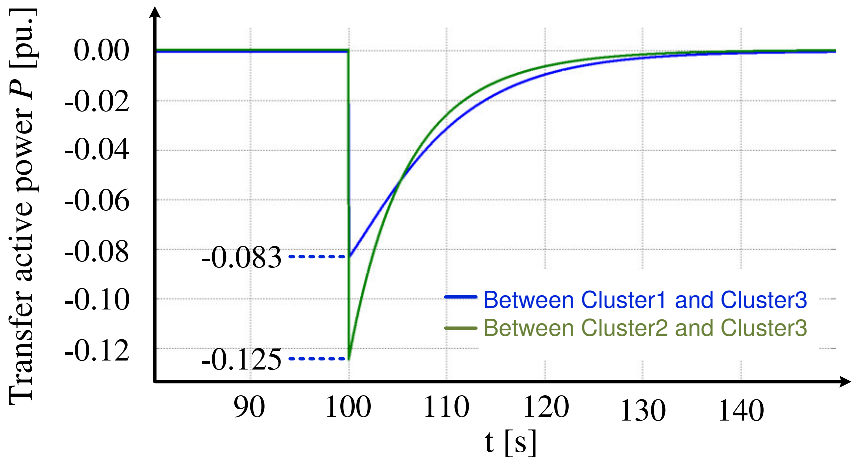


Fig. 4.16: Zoom on active power exchange between clusters during the first simulation event

B. Discussion on power systems frequency

Talking about power systems stability, it is necessary to observe power systems frequency, since it is a system state variable. The system frequency of the examined clustering system is shown in Fig. 4.17. In addition, the zoom of power systems frequency during the first simulation event is illustrated in order to show the characteristic of PC and SC during load change, as portrayed in Fig. 4.18.

- At 100s, the frequency drops due to the large load step in cluster3. All cluster controllers, which have horizontal control function, operate together in order to bring the frequency back to the nominal value after short time. This is more obvious in zoom figure.
- At 300s, new cluster reference value is reorganized. This leads to change the power balance of each cluster area. Obviously, this event causes a frequency dip as well. Nevertheless, the frequency dip is smaller than the previous event, because the change does not directly affect on unit level.
- At 500s, the DMS3 took over cluster2, since DMS2 is out of order. This event is directly impacted to unit level; the system frequency is thus changed. In this case, it is increased because the most change is effected on Gen12, which the generated power is decreased. Definitely, the proposed controller is able to bring the system frequency back to nominal value.

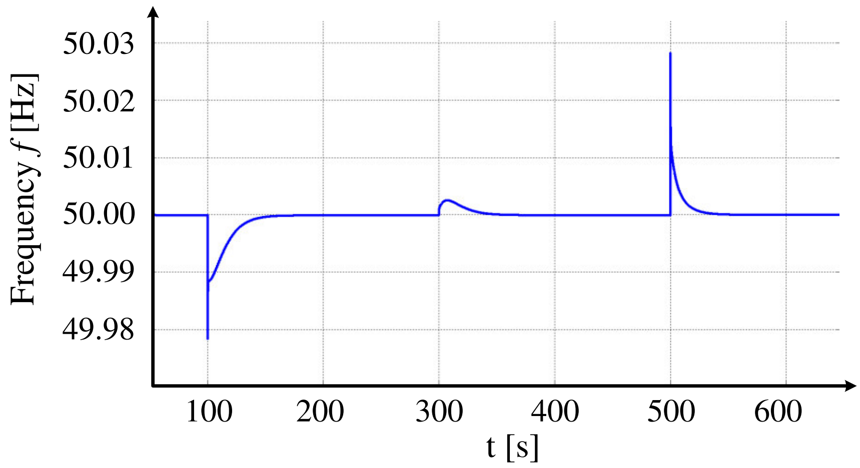


Fig. 4.17: Power systems frequency

To separate the behavior of PC and SC, the zoom of systems frequency during the step load in first simulation event is displayed in Fig. 4.18. The simulation result shows that the frequency dip is firstly stabilized to the stationary value; this is the function of PC. Afterwards, the SC is responded. It slowly brings the systems frequency back to nominal value.

The discussions based on power systems frequency show that the proposed horizontal cluster control application is able to maintain and recover the frequency to nominal value. It guarantees the stability of the cluster systems. In this section, the proposed cluster control is examined only in the part of horizontal control application. Therefore, the combination between vertical and horizontal application is provided and analyzed in the next section.

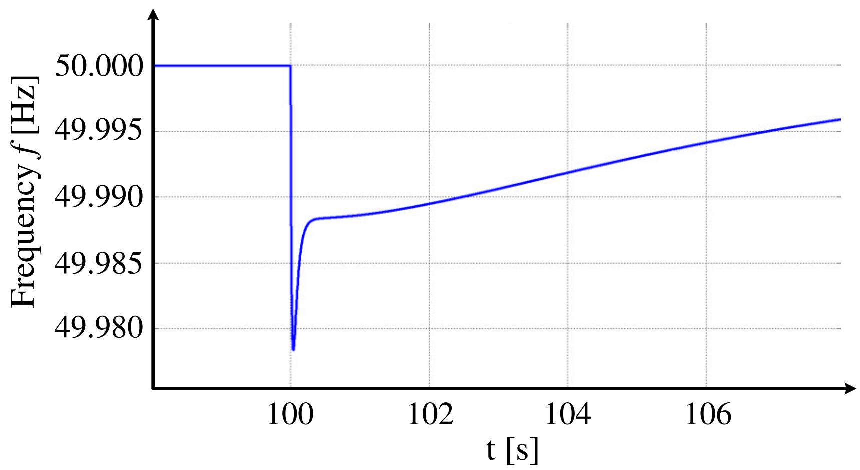


Fig. 4.18: Zoom on power systems frequency during the first simulation event

4.3.3 Case Study2 – Vertical and Horizontal Control Application

As the horizontal control- and the management application are examined and validated through previous case study, the vertical SC application is subsequently the main focus in this section. To verify the vertical control application, an examined cluster system of this operation mode is developed as illustrated in Fig. 4.19. The examined cluster system is commonly based on the same system from the previous case, but cluster5 is added into system in order to describe the behavior of multi-level interconnected cluster systems. Thus, the tested cluster systems are stated with two cluster levels, which are described as superordinate level and ordinate level. Cluster4 and cluster5 are declared as the superordinate level and cluster1, cluster2 and cluster3 are the ordinate cluster.

There are three interconnected positions in the examined system. Two are located in the subordinate level. They are located between cluster1-cluster3 and cluster2-cluster3. The other connection is between cluster3 and cluster5, which is stated as the connection between the different cluster levels. Obviously, the controller of each cluster is noticed by DMS, which contains the SC scheme as well. The cluster control scheme in this study is the combination between vertical and horizontal cluster control approach, as related to Fig. 4.7.

Similar to previous study, the tested system is a symmetrical system. The simulation is done on MATLAB/Simulink. The hybrid decoupling power flow analysis platform, the dynamic synchronous generator- and the inverter RMS model are utilized in this case study as well.

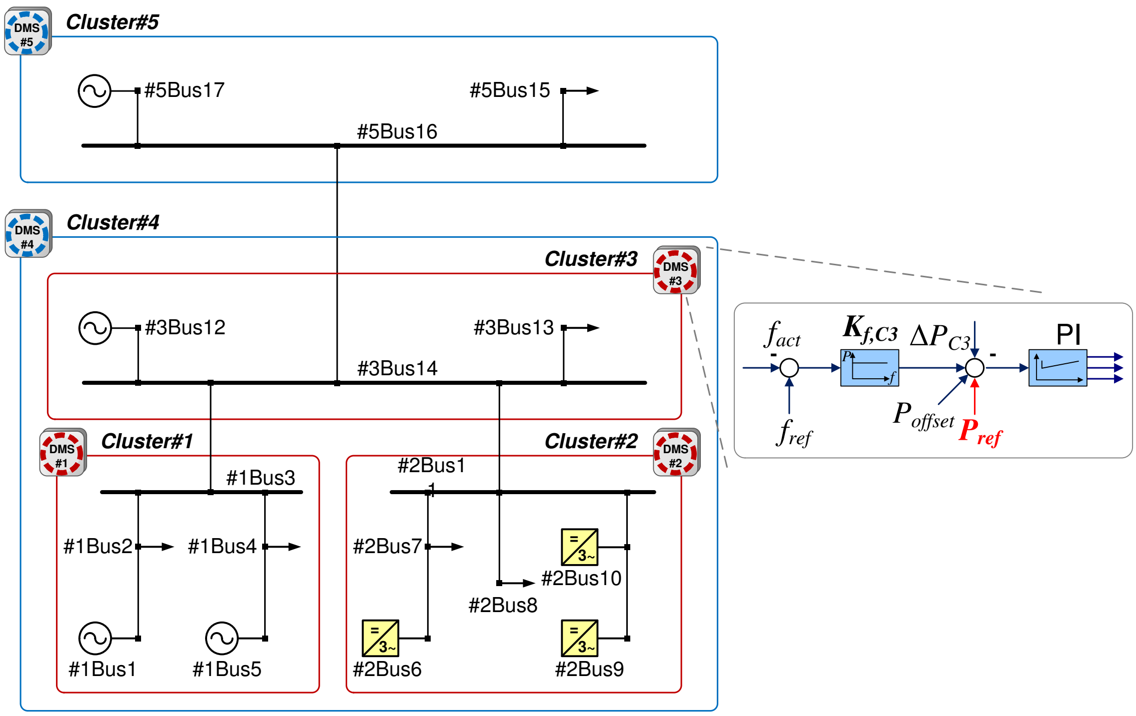


Fig. 4.19: Examined cluster system

The parameters for the examined power system are considered based on a low voltage network description, where rated voltage is 400 V_{L-L}; and rated frequency is 50 Hz. The reference values of each generator, inverter and applied load are detailed and illustrated in Table 4.3. Each bus is connected with 100m NAYY 4x50 SE cables; R_l = 0.772 Ω/km and X_l =0.083 Ω/km.

Table 4.3: Reference value of generator, inverter and load

		P_{ref} [pu.]		P_{load} [pu.]
Cluster1	Gen1	1.00	Load2	1.00
	Gen5	1.00	Load4	1.00
Cluster2	INV6	0.666	Load7	1.00
	INV9	0.666	Load8	1.00
	INV10	0.666		
Cluster3	Gen12	1.00	Load13	1.00
Cluster5	Gen17	1.00	Load15	1.00

The simulation events are given and divided into two parts in order to demonstrate the characteristic of horizontal and vertical control application. Firstly, at 200s, the step load is applied to load15. In this case, the power balance functionality of each cluster is tested as well as the frequency recovering function. Secondly, the power flow management function is examined at 500s. The power exchange reference values are defined and provided to all cluster in the event. The simulation details are summarized in Table 4.4.

Table 4.4: Overview of simulation events

Time [s]	Simulation events
200	Applying 0.16 pu. active power step load to cluster5 Load15
500	DMS4 has managed applied power of the subordinated clusters as following: • Cluster1 applying 0.08pu. • Cluster2 not needed to apply • Cluster3 applying 0.08pu.

As noted that this study is concerned on frequency control part, the following discussions are thus based on frequency, rated active power generation as well as exchanged active power between clusters. These results show that the proposed method has possibility to reverse power flow, which is expected in future power systems.

A. *Discussion on power generation and power exchange between cluster systems*

The discussion on this section is focused on power generation of each generating unit and active power exchanges between cluster systems. According to the power exchanges, there are three interconnected positions. Two are located in the ordinate level, which are located between cluster1-cluster3 and cluster2-cluster3. The other connection is between cluster3 and cluster5, which is stated as the connection between the different cluster levels.

In order to clarify the unit level characteristics, the results of all generating units are shown in Fig. 4.20, separated by cluster area. Additionally, the simulation results of power exchange between interconnected clusters are shown in Fig. 4.21. The discussion of each simulated event is listed as following:

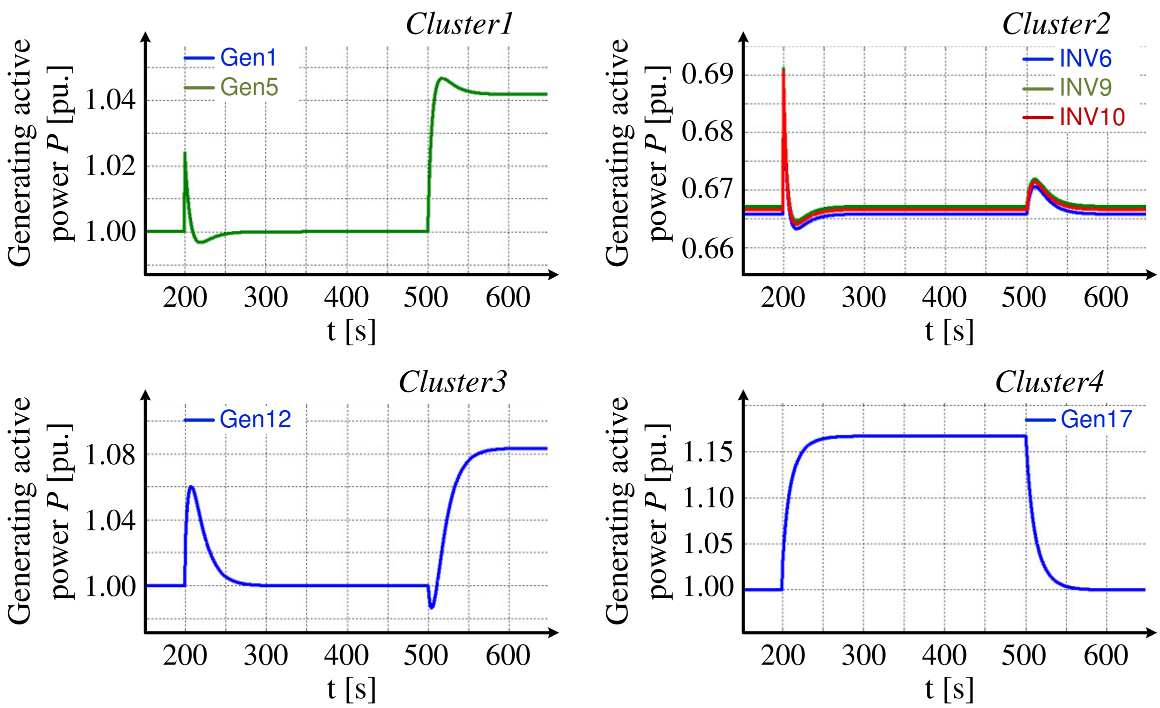


Fig. 4.20: Active power of each generating unit

- Before executing the simulation events, the power transfer and power generation are constant at the initial value.
- At 200s, 0.16 pu., the step load is applied to cluster5, load15. According to the grid code regulation, at the beginning of this period, all generation units have to support this load change. It is obvious in Fig. 4.20. All generating units on cluster1, cluster2 and cluster3 increase their generated power to support this load change. After that, they decrease the power and back to the nominal state when the generating unit on cluster5, Gen17 can support this change. It can be also noticed by the power exchange between clusters that there is no power transfer for this load change. This is the evidence that the proposed method is able to keep the balance of each cluster area.
- To verify the exchange power control function, the load change from first events is decided to be supported by cluster4. Therefore, at 500s, DMS4 provides a new active

power reference point to subordinate clusters. Cluster1 and cluster3 have to apply 0.08 pu., but cluster2 does not have to support this change. Thus, the simulation results that Gen17 decreases the generated power and other generating units on cluster1 and cluster3 take place for it. Since power transfer from cluster2 is not requested, therefore, all generating power remains as nominal value. It is also obvious in Fig. 4.21 that the supported power, 0.16 pu., is flow into cluster5. The supporting power is generated from subordinated cluster level; cluster1 and cluster3 generate 0.08 pu. each. This shows that the proposed method is able to reverse power flow process.

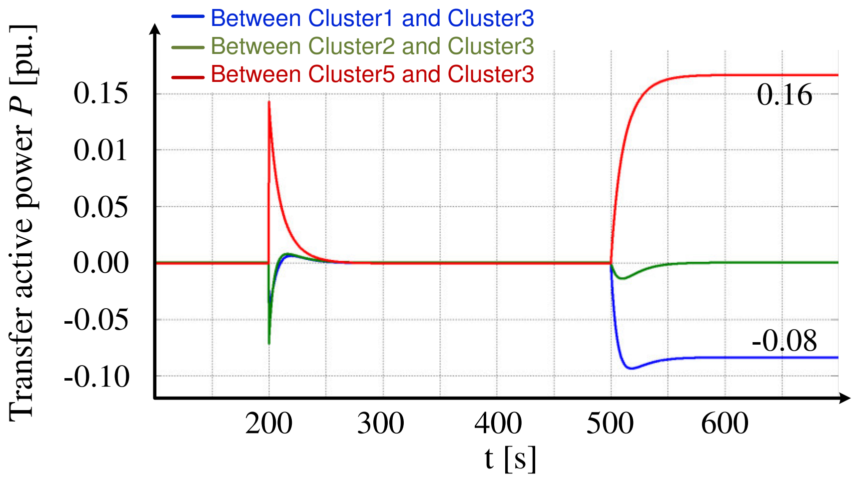


Fig. 4.21: Active power exchange between clusters system

After discussion about power generation and power exchange between clusters, the simulation results validate the power control scheme of horizontal and vertical application. Furthermore, the power sharing on unit level is also worked properly.

B. Discussion on power systems frequency

In order to indicate power systems stability, it is important to examine power systems frequency. The system frequency of the examined power system is shown in Fig. 4.22. In addition, the zoom of power systems frequency at the first simulation event is illustrated in order to show the PC and SC behavior, as portrayed in Fig. 4.23.

- At 200s, the frequency drops due to the large load step in cluster5. All cluster controllers, which contains vertical and horizontal control function, operate together in order to bring the frequency back to the nominal value after short time. This is more obvious in the zoom figure.
- At 500s, the DMS4 has managed a new reference value. This event leads to have a frequency dip as well. Nevertheless, the frequency dip is rather smaller than the

previous event, because the change does not directly affect on unit level. Definitely, the proposed controller is able to bring the system frequency back to nominal value.

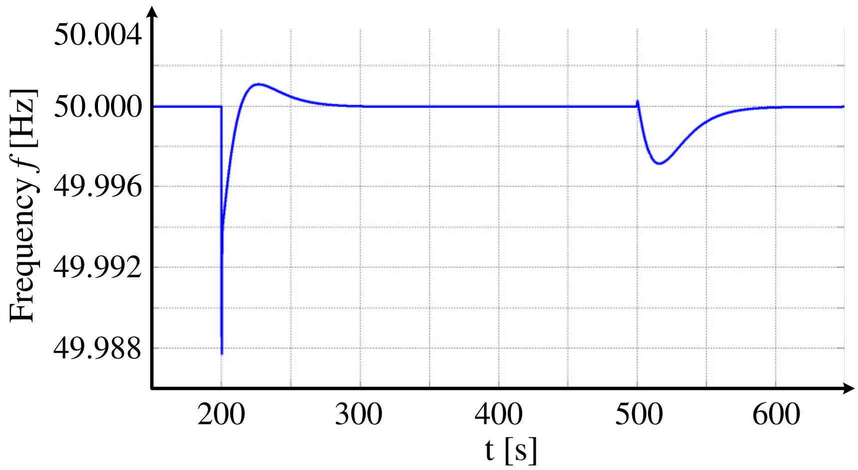


Fig. 4.22: Power systems frequency

To point out the behavior of PC and SC, the zoom of systems frequency during the first simulation event is displayed in Fig. 4.23. The result shows that the PC firstly stabilizes the frequency dip to the stationary value. Afterwards, the SC is responded to bring the system frequency back to its nominal value, which is according to the grid regulation. As a result, the simulation results are the proof of the proposed vertical and horizontal control applications. Moreover, it can be implied that the introduced control method provides the coexistence with the conventional control strategy. This assures the stability of the entire power systems.

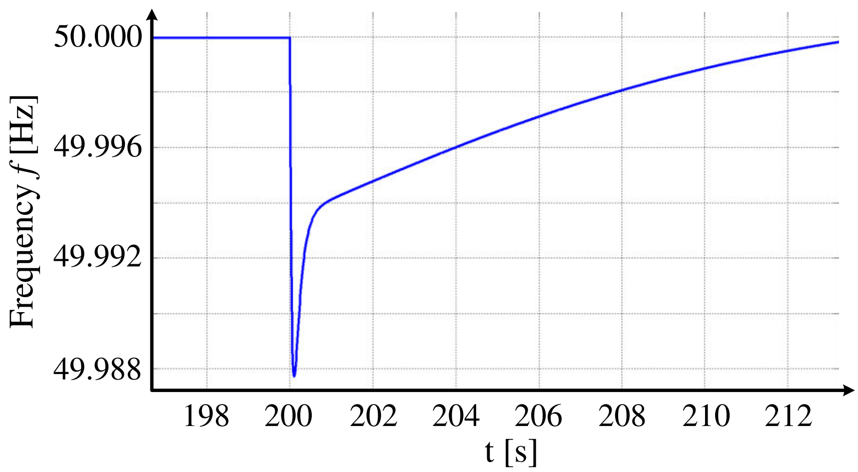


Fig. 4.23: Zoom on power systems frequency during the first simulation event

4.4 Summary

In this chapter, the vertical and horizontal control applications are introduced as an essential control function for interconnected clusters system. The operation of horizontal control application represents the conventional character of transmission system. The vertical control application complements the expectations of future energy power supply system e.g. active interaction between different cluster network levels. The proof of this condition is indicated in the verification case studies. As both control applications are evolved based on recycling conventional control approach; thus, the automated control ability of PC and SC, which is obvious in transmission network, is subsequently transferred to distribution network. This automated ability allows moreover an important key to move towards future oriented smart supply system.

To fulfill automated control function, the supervisory control level or TC has to be subsequently down to the distribution network. Regarding this point of view, TC becomes a part of cluster controller unit or DMS as control supervisory. Fig. 4.24 illustrates the proposed control applications of smart supply system based on clustering power systems philosophy. As emphasized that the bottom-up approach is a key to success in empowering distribution network down to prosumer unit. This fact also represents in the case of downsized TC implementation. Generally, one application of TC is the supervisory of controller e.g. providing the optimum operating point. Hence, the downsized of TC is needed for the cluster management. Additionally, due to the penetration of DG units, the system management, e.g. load and power generation forecasting, becomes an important issue for distribution network as well. It must be noted that the PC, which is implemented in all generation units, and the communication system in Fig. 4.24 are neglected to display.

A key to achieve the management tasks including supervisory of cluster control application is a power system analysis or rather power flow study. A cluster analysis strategy is needed to figure out together with the development of cluster power flow analysis. Since the clustering concept is contributed the system network in many interconnected cluster areas. Furthermore, its operation is targeted to process based on each cluster area. This directly leads a decoupling functionality for the cluster analysis strategy.

To handle with decoupling issue, a hybrid calculation approach is proposed because it offers a possibility to integrate a character of interconnected clusters into the analysis. Consequently, the cluster analysis can be achieved in a decoupling way. The character of distribution network has to be also taken into account, as the target of clustering power systems is to empower distribution network. The character of distribution network is dominated by the unbalanced condition e.g. multi-phase feeder system. Moreover, the penetration of DG units can cause the unbalanced condition as well, e.g. single phase feed in of home PV systems. To solve load flow study with unbalanced condition, an asymmetrical analysis algorithm, sequence hybrid and three-phase four-wire hybrid, is required; both are developed based on a difference issue of load flow study. As a result of cluster analysis, the cluster area oriented distribution system is able to manage itself in an automatic way similar to TSO. The development of proposed hybrid analysis algorithm including background knowledge is elucidated step by step in the following chapter.

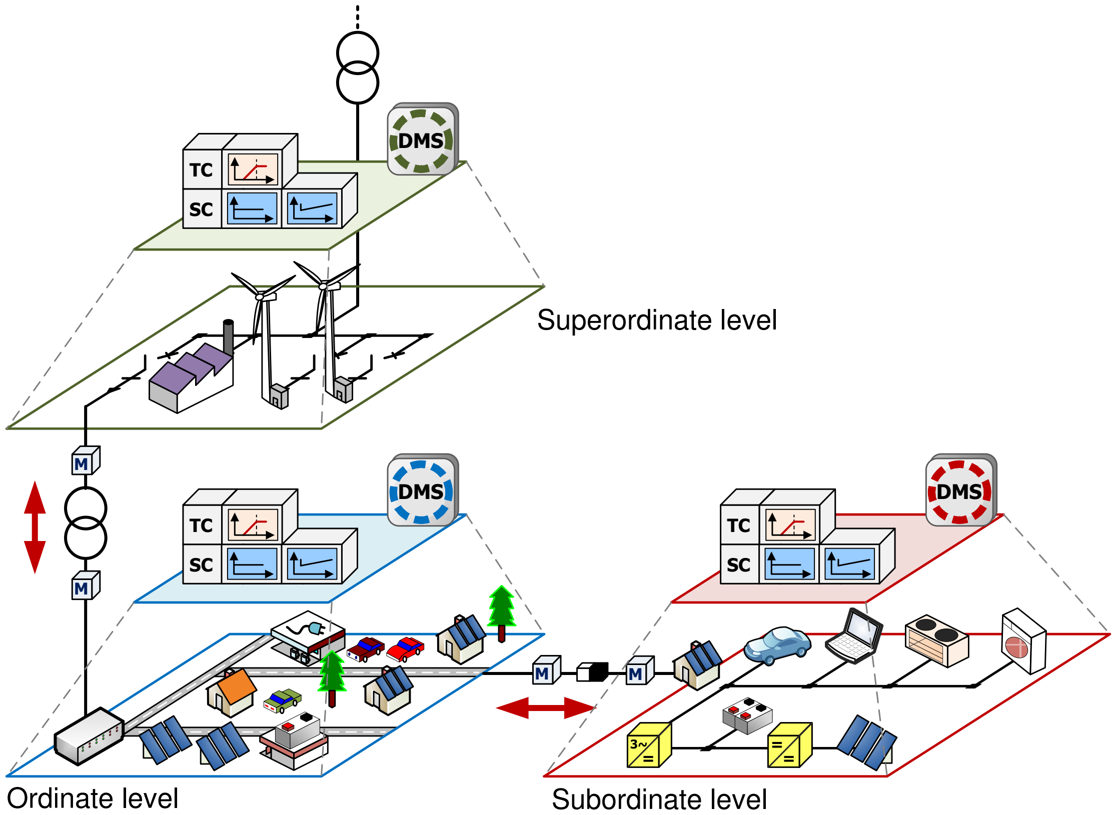


Fig. 4.24: Multi-level cluster management strategy based on bottom-up approach

5. Cluster System Analysis Method

Enabling the automated active control mode in distribution network in a compatible way as conventional interconnected grids system, the TC operation is subsequently considered to be downsized to the distribution level as well as the common function of power systems management. To accomplish it, the power systems analysis of cluster network is cautiously concerned, because it is a fundamental function of the management approach.

Considering the cluster network, which results in multi-level interconnected clusters, this can increase the complexity of systems analysis due to the flexibility adaptation of cluster network. Therefore, a decoupling analysis approach for each cluster system is taken into account. Subsequently, load flow analysis techniques are examined in order to find the proper solution to deal with decoupling analysis issue.

As a result, a hybrid calculation technique is promoted as an approach for cluster system analysis, since it can combine a behavior of interconnected clusters into the analysis. To figure out cluster system analysis method, this chapter firstly provides a strategy for cluster analysis. Secondly, the conventional load flow analysis methods are discussed. Next, the hybrid calculation method is proposed and its derivation is described in detail. Finally, privileges of applying hybrid technique with cluster system are given.

5.1 Cluster System Analysis Strategy

The clustering power systems philosophy structures the network in multi-level interconnected clusters. The vertical- and horizontal cluster control applications based on conventional control approach are proposed to be the strategy for enabling the automated active control area in the distribution network and to allow the bottom-up control processing to meet the operation of transmission systems with compatibility. To move towards the development of cluster control and to fulfill the cluster operation, the roles of supervisory control level and cluster management are considered. To succeed in those mentioned issues, a cluster system analysis is directly concerned as a key subject, since the power systems analysis is a main function of system planning, optimization, as well as the regulation of subordinated control applications (vertical and horizontal control application).

In order to figure out the analysis strategy for interconnected cluster systems, an aim of cluster management and operation strategy is represented in Fig. 5.1. The interconnected cluster systems are commonly introduced with three different cluster levels, i.e. superordinate, ordinate and subordinate level. Fig. 5.1 shows that one ordinate cluster is targeted to be an example area, which the cluster operation process is intended to function within cluster area itself. According to this operation target, it can be implied that the information of interconnected cluster nodes are needed to exchange. Regarding cluster network structure and operation target, they lead to an explicit strategy for cluster management process. Those also affect straight into the cluster systems analysis strategy. It means that each single cluster area must perform the load flow analysis in a decoupling way to fulfill the aim of cluster operation.

To achieve the decoupling analysis of interconnected cluster networks, the interaction behavior from other clusters, i.e. superordinate and subordinate cluster, have to be concerned. The power system state variables, frequency and voltage, are subsequently considered as the best way for describing the interaction character, since they are fundamental variables to express and identify the power network. Deliberating between two state variables, it is obvious that the voltage is a proper state variable for load flow study. An explanation can be referred to a basic of power flow study, which a direction of power flow in tie line or between two nodes is commonly described by node voltage [4], and [8]. Hence, the voltages from interconnected clusters nodes are only concerned for the decoupling analysis purpose. For example in Fig. 5.1, the high side voltage of distribution transformer is used to describe the behavior of superordinate level. Similarly, the behavior of subordinate can be described by the voltage at house connection point. Those voltages must be involved in the analysis of ordinate cluster. Then, the ordinate cluster can execute the load flow analysis based on its area itself.

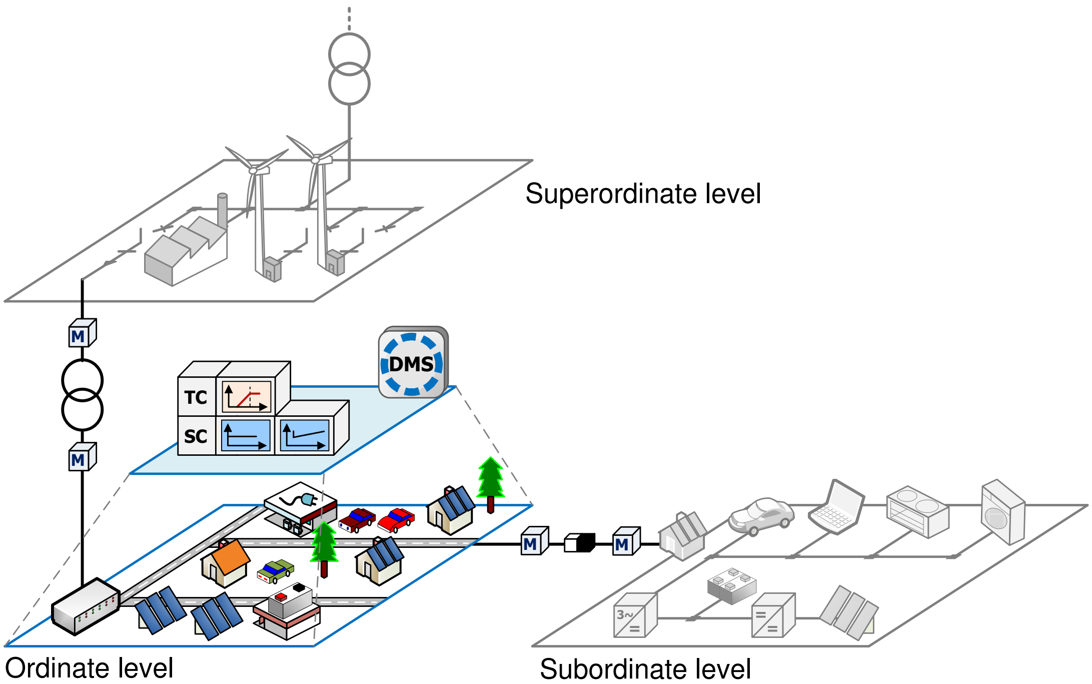


Fig. 5.1: Cluster operation and management strategy

On the same hand, including the interaction from other connected clusters into decoupling cluster analysis further requires a linkage of connected clusters nodes to maintain a physical behavior of power flow. Then, an analysis network model must be extended by adding the linkage of connected clusters nodes. As the case in Fig. 5.1, the distribution transformer and the line to house connection must be included into the analysis network model or bus admittance model of ordinate cluster network.

Even though the interconnected voltages can describe the character of connected cluster systems, a reliable decoupling analysis also depends on time synchronization. For instance, if there is a sampling time mismatch between measurements, i.e. the meter of distribution transformer and the meter of house connection point, it is true that the results of decoupling cluster analysis will be wrong. For this reason, the time synchronization of transmitting the measured values becomes an important factor for the cluster systems analysis.

To conclude, the cluster analysis method has to perform in a decoupling way and it must deal with more than one fixed voltage source in order to represent a behavior of interconnected clusters. Next, an investigation of conventional load flow analysis method is elucidated in order to find a proper analysis method for cluster network.

5.2 Conventional Load Flow Analysis Methods

As the voltages of interconnected clusters nodes are considered and utilized for describing the character of connected clusters to execute the decoupling analysis approach, therefore, the cluster analysis method must be able to solve the network with more than one fixed voltage source. To find out the proper analysis method, this section is initially donated for the discussion based on conventional load flow methods. Those clarify and prove a guideline for the development of cluster analysis method. A current injection method and a Newton-Raphson method are selected for an investigation, since both are well-known methods in conventional power flow study.

5.2.1 Current Injection Method

The current injection method is one of the classical analysis methods for the power flow calculation, and this method is still able to analyze the complex and smart network, which the intelligent components, e.g. inverter, can be considered as a current source. Fig. 5.2. illustrates an overview of power systems, which can be analyzed by the current injection method. The main idea of this method is to build up the current summation, which each bus current is injected and defines the current direction by using a mathematic sign. The positive current is the current flowing into the bus. On the other hand, the negative current is flown out of the bus.

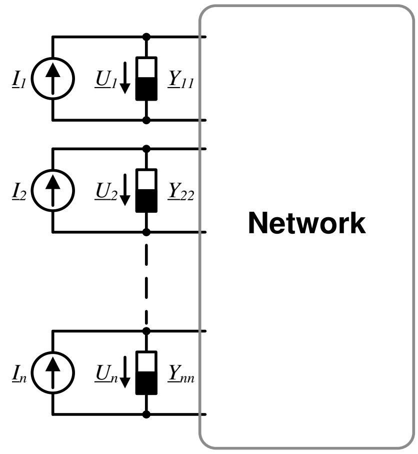


Fig. 5.2: Current source network

To complete this analysis method, a bus admittance matrix has to be defined. The bus admittance matrix describes the system structure in a single line diagram by using the π-equivalent to represent it in a mathematical model. Thus, this method is implemented by solving for the complex bus voltage equation in Eq. (5.1).

$$\begin{bmatrix} \underline{U}_1 \\ \underline{U}_2 \\ \vdots \\ \underline{U}_n \end{bmatrix} = \begin{bmatrix} \underline{Y}_{11} & \underline{Y}_{12} & \cdots & \underline{Y}_{1n} \\ \underline{Y}_{21} & \underline{Y}_{22} & \cdots & \underline{Y}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \underline{Y}_{n1} & \underline{Y}_{n2} & \cdots & \underline{Y}_{nn} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \underline{I}_1 \\ \underline{I}_2 \\ \vdots \\ \underline{I}_n \end{bmatrix} \tag{5.1}$$

Where n is the number of buses in the power systems, the complex vector of terminal voltages is declared by $\underline{U}_i$ (i=1,2,3,…,n). The complex vector of bus currents is $\underline{I}_i$ (i=1,2,3,…,n). The self-admittance of bus i is $\underline{Y}_{ii}$ (i=1,2,3,…,n), which is at the diagonal elements. Lastly, the mutual admittance between buses i and k is $\underline{Y}_{ik}$ (i, k=1,2,3,…,n).

Performing load flow analysis, a current iteration process is utilized to reach a minimum error allowance of power mismatch. After the power flow problem is solved, the load flow solution is calculated through Eq. (5.2).

$$[\underline{S}_n] = diag[\underline{U}_n] \cdot [\underline{I}_n]^* \tag{5.2}$$

Regarding the current injection method, the model, e.g. a generator model or an inverter model, which has a characteristic as a swing generation unit, is compulsory. Otherwise, there is no reference voltage bus in pure current source network. Hence, it is obvious that the current injection method is unsuitable for the cluster system analysis strategy. There is no chance to integrate the behavior of interconnected cluster, which is described by voltage.

5.2.2 Newton-Raphson Method

Generally, the Newton-Raphson method is a powerful iteration technique for solving linear equations. Therefore, the Newton-Raphson method is commonly used and applied in load flow study, because it can find the solution with a very good convergent characteristic of the system. As the well-known numerical method, a description of its iterative technique can be regularly found in almost of power system analysis books e.g. [8] and [138]. A power flow solution is usually solved by finding a minimum error allowance of power mismatches as a tolerance value. To find the power mismatches based on Newton-Raphson method, the mismatch equation is expressed in Eq. (5.3).

$$\begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix} = \begin{bmatrix} J_{11} = \dfrac{\partial P_i}{\partial e_i} & J_{12} = \dfrac{\partial P_i}{\partial f_i} \\ J_{21} = \dfrac{\partial Q_i}{\partial e_i} & J_{22} = \dfrac{\partial Q_i}{\partial f_i} \end{bmatrix} \cdot \begin{bmatrix} \Delta e_i \\ \Delta f_i \end{bmatrix} \; ; \; \underline{U}_i = e_i + jf_i \tag{5.3}$$

Where i is the bus number in the power systems (i=1,2,3,…,n). A power mismatches vector consists of ΔP and ΔQ. The correction vector contains a correction of real part (Δe), and imaginary part (Δf) of node voltage. The Jacobian matrix is labeled by J.

To clarify the Newton-Raphson load flow analysis, its iteration process flow chart is introduced in Fig. 5.3 [8]. To start the process, an initial bus voltage has to be given to generate initial active power and initial reactive power. Afterwards, the power mismatch is calculated by comparing with desired power values. Subsequently, the voltage correction vector is obtained through Eq. (5.3) in order to update new bus voltage, the active power and the reactive power, respectively. The calculation is finally stopped, when the power mismatch values are in the error allowance area.

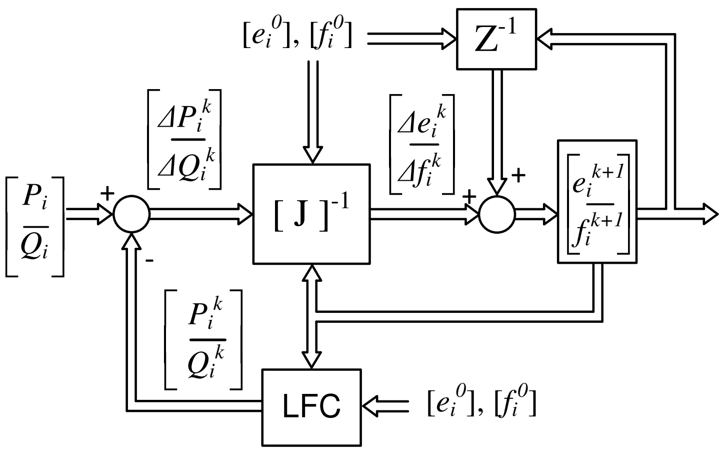


Fig. 5.3: Iteration process of Newton-Raphson load flow analysis [8]

Even though, the Newton-Raphson load flow analysis is a powerful method regarding a very good convergent characteristic, a high computational time in the load flow calculation is occurred due to the creation of Jacobian matrix in each single iteration process. Conversely to the Newton-Raphson method, the current injection method solves the power flow problem with simply current source model and fast iteration computational process. However, it has slower convergent characteristic than Newton-Raphson method.

Considering a compatibility with the cluster system analysis strategy, the conventional Newton-Raphson method can deal with only one fixed voltage source, called slack node. This conventional approach means that it is not able to analyze the interconnected clusters network in a decoupling way, where the cluster connection voltages must be included to describe the behavior of neighbor connected clusters. However, it can be further developed to handle with more than one fixed voltage source, since the correction vector and the power mismatch equation is basically described by the voltage value.

Up to this point, the Newton-Raphson method is the first load flow analysis option, but the high computational complexity must be concerned and foreseen, as it can cause a problem due to a huge system network analysis.

5.3 Hybrid Calculation Method

In previous section, two classical load flow analysis methods, the current injection and the Newton-Raphson, are discussed. As the current injection method is not suitable for the cluster system analysis strategy due to the need of swing generator model, it is consequently clear that this method is not proper for the cluster system analysis strategy. However, this current injection method provides a huge advantage regarding simple and fast iteration computational process. Moreover, the intelligent component can be described by simply current source model, this must be foreseen that this method also provides a benefit to support a future electrical component. On the other hand, the Newton-Raphson method has the ability to solve the approach of cluster analysis, but the computational time is concerned as a problem.

According to those advantages and disadvantages, the hybrid calculation technique is further examined and taken into account. It must be firstly mentioned that the hybrid calculation is not a new technique. It is already known in the mathematical method, but it is not famous in the field of load flow analysis. Its usage can be found on [134] and [135].To clarify the hybrid technique based on power systems network, a network with mixing type of input sources, voltage and current, is introduced as in Fig. 5.4.

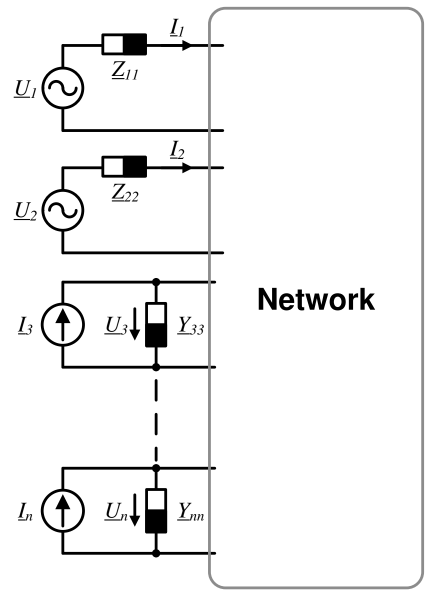


Fig. 5.4: Mixing of voltage- and current source network

Regarding the illustrated mixing of voltage- and current source network or the hybrid network, it can be described in mathematical model in the term of complex impedance ($\underline{Z}$), complex admittance ($\underline{Y}$), and complex factor ($\underline{x}$). This mixing mathematic network model description can be done, because the network has a linearity property. As a result, the general bus admittance matrix can be written in Eq. (5.4), where n is the number of buses in the system network.

$$\begin{bmatrix} \underline{U}_1 \\ \underline{U}_2 \\ \underline{I}_3 \\ \vdots \\ \underline{I}_n \end{bmatrix} = \begin{bmatrix} \underline{Z}_{11} & \underline{x}_{12} & \cdots & & \underline{x}_{1n} \\ \underline{x}_{21} & \underline{Z}_{22} & \cdots & & \underline{x}_{2n} \\ \vdots & \vdots & \underline{Y}_{33} & \cdots & \underline{Y}_{3n} \\ & & \vdots & \ddots & \vdots \\ \underline{x}_{n1} & \underline{x}_{n2} & \underline{Y}_{n3} & \cdots & \underline{Y}_{nn} \end{bmatrix} \cdot \begin{bmatrix} \underline{I}_1 \\ \underline{I}_2 \\ \underline{U}_3 \\ \vdots \\ \underline{U}_n \end{bmatrix} \tag{5.4}$$

The Eq. (5.4) is a general description of hybrid equation. It can be noticeably understood that the cluster systems analysis strategy can be fulfilled and solved by the hybrid calculation approach. Because the voltage can be considered as interconnected clusters and can be described more than one source. Furthermore, any intelligent component, e.g. inverter, can be equipped in the hybrid calculation approach on the part of current sources. Thinking over computational time in iteration process, the load flow solution can be basically accomplished by current iteration process. According to those facts, the hybrid technique is subsequently considered as a key method for cluster analysis method.

To complete the hybrid load flow calculation, a hybrid matrix must be cautiously examined, since it is a key element to define the relation of mixing source network. The hybrid matrix can be divided into two types: impedance hybrid matrix $[\underline{H}_Z]$ and admittance hybrid matrix $[\underline{H}_Y]$. The difference between both types is the order of the first matrix element. If the first element is written in an impedance form, it is called as an impedance hybrid matrix. On the other hand, if the first element is written in admittance form, it is named as an admittance hybrid matrix. In the following section, the derivation of two types of hybrid matrix is presented. This clarifies a different application of both types.

To summarize, an ability to deal with more than one voltage in the hybrid calculation method gives an opportunity to analyze the cluster network in a decoupling way. The behavior of interconnected cluster can be integrated into each single cluster analysis as expected in cluster analysis strategy section. Additionally, the simple current iteration process of hybrid calculation ensures fast computational time. To forward those advantages, a cluster load flow analysis algorithm is developed under hybrid calculation method.

5.3.1 Preparation Process for Hybrid Matrix Calculation

As mentioned that the hybrid matrix can be described the network system, which consists of the voltage source and the current source in the same system. There are two types of hybrid matrix, i.e. impedance and admittance hybrid matrices. Hence, the derivation of both hybrid matrix types is noteworthy to figure out.

Commonly, the bus admittance matrix is utilized for describing any power systems network. Nevertheless, the hybrid network is relied on the type of input source; therefore, the bus admittance matrix must be sorted regarding the group of voltage source and current source. In other words, it can be implied to the group of known and unknown parameters. In this thesis, all known parameters are described with subscript index *K*. In the opposite way, all unknown parameters are written by subscript index *U*. If the group of unknown voltage nodes is declared by vector $[\underline{U}_U]$ and the group of known voltage nodes is declared by vector $[\underline{U}_K]$. Consequently, a known current vector $[\underline{I}_K]$ and an unknown current vector $[\underline{I}_U]$ are directly related to $[\underline{U}_U]$ and $[\underline{U}_K]$, respectively. As a result, the sorted bus admittance matrix can be written in Eq. (5.5).

$$\begin{bmatrix} [\underline{I}_K] \\ [\underline{I}_U] \end{bmatrix} = \begin{bmatrix} [\underline{Y}_{AA}] & [\underline{Y}_{AB}] \\ [\underline{Y}_{BA}] & [\underline{Y}_{BB}] \end{bmatrix} \cdot \begin{bmatrix} [\underline{U}_U] \\ [\underline{U}_K] \end{bmatrix} \tag{5.5}$$

Where the admittance group $[\underline{Y}_{AA}]$ is a square admittance matrix, which is related to unknown voltage vector $[\underline{U}_U]$. Similarly, the square matrix $[\underline{Y}_{BB}]$ is linked with the known voltage vector $[\underline{U}_K]$. The rest parts of the sorted admittance matrix are defined by matrix $[\underline{Y}_{AB}]$ and $[\underline{Y}_{BA}]$, respectively, and those two are the transposed matrices of each other.

The sorted admittance matrix is a key element for hybrid matrix calculation. Thus, it is significant to have a look on how the buses admittance matrix is sorted. Fig. 5.5 illustrates a small example network. The examined network consists of five buses; the admittance value of each cable is labeled with $\underline{Y}$. Consequently, the admittance matrix of examined network can be written in Eq. (5.6).

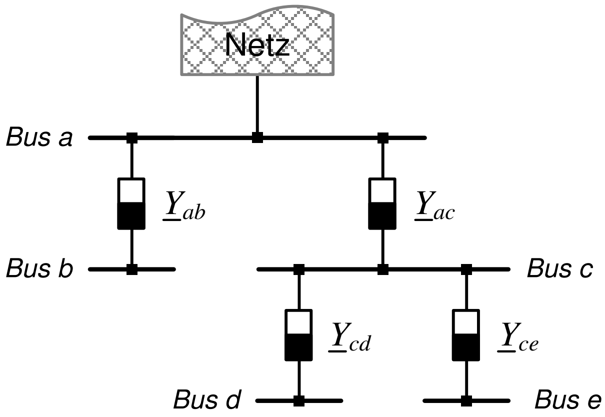


Fig. 5.5: Examined five buses system for sorted bus admittance matrix

$$\begin{bmatrix} \underline{I}_a \\ \underline{I}_b \\ \underline{I}_c \\ \underline{I}_d \\ \underline{I}_e \end{bmatrix} = \begin{bmatrix} \underline{Y}_{ab}+\underline{Y}_{ac} & -\underline{Y}_{ab} & -\underline{Y}_{ac} & 0 & 0 \\ -\underline{Y}_{ab} & \underline{Y}_{ab} & 0 & 0 & 0 \\ -\underline{Y}_{ac} & 0 & \underline{Y}_{ac}+\underline{Y}_{cd}+\underline{Y}_{ce} & -\underline{Y}_{cd} & -\underline{Y}_{ce} \\ 0 & 0 & -\underline{Y}_{cd} & \underline{Y}_{cd} & 0 \\ 0 & 0 & -\underline{Y}_{ce} & 0 & \underline{Y}_{ce} \end{bmatrix} \cdot \begin{bmatrix} \underline{U}_a \\ \underline{U}_b \\ \underline{U}_c \\ \underline{U}_d \\ \underline{U}_e \end{bmatrix} \tag{5.6}$$

Assuming the unknown voltage vector [$\underline{U}_U$] is the voltage combination of bus *a* and *c*. The known voltage vector [$\underline{U}_K$] is the voltage combination of bus *b*, *d* and *e*. Both voltage groups are illustrated in Eq. (5.7).

$$[\underline{U}_U] = \begin{bmatrix} \underline{U}_a \\ \underline{U}_c \end{bmatrix}, \quad [\underline{U}_K] = \begin{bmatrix} \underline{U}_b \\ \underline{U}_d \\ \underline{U}_e \end{bmatrix} \tag{5.7}$$

To obtain the sorted matrix as in Eq. (5.5), the bus admittance matrix in Eq. (5.6) has to be rearranged in order to maintain the relation of examined system regarding the voltage group of Eq. (5.7). Thus, the new bus admittance matrix can be stated in Eq. (5.8).

$$\begin{bmatrix} \underline{I}_a \\ \underline{I}_c \\ \underline{I}_b \\ \underline{I}_d \\ \underline{I}_e \end{bmatrix} = \begin{bmatrix} \underline{Y}_{ab}+\underline{Y}_{ac} & -\underline{Y}_{ac} & -\underline{Y}_{ab} & 0 & 0 \\ -\underline{Y}_{ac} & \underline{Y}_{ac}+\underline{Y}_{cd}+\underline{Y}_{ce} & 0 & -\underline{Y}_{cd} & -\underline{Y}_{ce} \\ -\underline{Y}_{ab} & 0 & \underline{Y}_{ab} & 0 & 0 \\ 0 & -\underline{Y}_{cd} & 0 & \underline{Y}_{cd} & 0 \\ 0 & -\underline{Y}_{ce} & 0 & 0 & \underline{Y}_{ce} \end{bmatrix} \cdot \begin{bmatrix} \underline{U}_a \\ \underline{U}_c \\ \underline{U}_b \\ \underline{U}_d \\ \underline{U}_e \end{bmatrix} \tag{5.8}$$

The matrix in Eq. (5.8) is called the sorted admittance matrix and ready to be separated as in Eq. (5.5). The matrix element, [$\underline{Y}_{AA}$], [$\underline{Y}_{AB}$], [$\underline{Y}_{BA}$], and [$\underline{Y}_{BB}$] can be attained as illustrated in Eq. (5.9).

$$\begin{aligned} \left[\underline{Y}_{AA}\right] &= \begin{bmatrix} \underline{Y}_{ab}+\underline{Y}_{ac} & -\underline{Y}_{ac} \\ -\underline{Y}_{ac} & \underline{Y}_{ac}+\underline{Y}_{cd}+\underline{Y}_{ce} \end{bmatrix}, & \left[\underline{Y}_{AB}\right] &= \begin{bmatrix} -\underline{Y}_{ab} & 0 & 0 \\ 0 & -\underline{Y}_{cd} & -\underline{Y}_{ce} \end{bmatrix} \\ \left[\underline{Y}_{BA}\right] &= \begin{bmatrix} -\underline{Y}_{ab} & 0 \\ 0 & -\underline{Y}_{cd} \\ 0 & -\underline{Y}_{ce} \end{bmatrix}, & \left[\underline{Y}_{BB}\right] &= \begin{bmatrix} \underline{Y}_{ab} & 0 & 0 \\ 0 & \underline{Y}_{cd} & 0 \\ 0 & 0 & \underline{Y}_{ce} \end{bmatrix} \end{aligned} \tag{5.9}$$

Obviously, [$\underline{Y}_{AA}$] and [$\underline{Y}_{BB}$] are square matrix, which their matrices dimensions are depended on the size of voltage vector [$\underline{U}_U$] and [$\underline{U}_K$], respectively. Moreover, it can be noticed that [$\underline{Y}_{AB}$] and [$\underline{Y}_{BA}$] are the transpose matrix of each other. Those four matrices are used to compute the impedance- and admittance hybrid matrices. The calculation method of both matrix types is elaborated in the following part.

5.3.2 Impedance Hybrid Matrix

Firstly, the calculation method of impedance matrix [$\underline{H}_Z$] is elucidated. As the first element of matrix is defined by impedance form, thus, the general target equation of impedance hybrid matrix can be given as in Eq. (5.10).

$$\begin{bmatrix} [\underline{U}_U] \\ [\underline{I}_U] \end{bmatrix} = [\underline{H}_Z] \cdot \begin{bmatrix} [\underline{I}_K] \\ [\underline{U}_K] \end{bmatrix} \tag{5.10}$$

Where, the known voltage node vector [$\underline{U}_K$] and the known current vector [$\underline{I}_K$] are arranged to the right hand side or input side. In order to figure out how to calculate this matrix, the first row of the sorted admittance matrix in Eq. (5.5) is considered firstly. Then, the known current vector equation is obtained as

$$[\underline{I}_K] = [\underline{Y}_{AA}][\underline{U}_U] + [\underline{Y}_{AB}][\underline{U}_K] \tag{5.11}$$

In order to achieve the first row of impedance hybrid matrix in Eq. (5.10), Eq. (5.11) has to be rearranged. The unknown voltage vector [$\underline{U}_U$] is moved to the left side, so it can be written as

$$[\underline{U}_U] = [\underline{Y}_{AA}]^{-1}[\underline{I}_K] - [\underline{Y}_{AA}]^{-1}[\underline{Y}_{AB}][\underline{U}_K] \tag{5.12}$$

Next, considering the unknown current vector [$\underline{I}_U$], where is located at the second row in Eq. (5.5).

$$[\underline{I}_U] = [\underline{Y}_{BA}][\underline{U}_U] + [\underline{Y}_{BB}][\underline{U}_K] \tag{5.13}$$

To accomplish the second row of impedance hybrid matrix equation, the unknown voltage vector [$\underline{U}_U$] in Eq. (5.13) has to be eliminated by substituting it with Eq. (5.12). Then, the result shows in Eq. (5.14).

$$[\underline{I}_U] = [\underline{Y}_{BA}][\underline{Y}_{AA}]^{-1}[\underline{I}_K] - \left\{ [\underline{Y}_{BB}] - [\underline{Y}_{BA}][\underline{Y}_{AA}]^{-1}[\underline{Y}_{AB}] \right\} \cdot [\underline{U}_K] \tag{5.14}$$

Combining Eq. (5.12) and Eq. (5.14), and arranging them in matrix form, the impedance hybrid matrix equation can be found.

$$\begin{bmatrix} [\underline{U}_U] \\ [\underline{I}_U] \end{bmatrix} = \begin{bmatrix} [\underline{Y}_{AA}]^{-1} & -[\underline{Y}_{AA}]^{-1}[\underline{Y}_{AB}] \\ [\underline{Y}_{BA}][\underline{Y}_{AA}]^{-1} & [\underline{Y}_{BB}] - [\underline{Y}_{BA}][\underline{Y}_{AA}]^{-1}[\underline{Y}_{AB}] \end{bmatrix} \cdot \begin{bmatrix} [\underline{I}_K] \\ [\underline{U}_K] \end{bmatrix} \tag{5.15}$$

Eq. (5.15) is the general equation of impedance hybrid matrix based on the sorted admittance matrix. It can be noticed that the first matrix element is described by the impedance form.

5.3.3 Admittance Hybrid Matrix

On the other hand, the hybrid matrix can also be derived in the opposite way, which it is named as the admittance hybrid matrix [$\underline{H}_Y$]. It is clear that the first matrix element is the admittance value. The general target equation of admittance hybrid matrix can be written as portrayed in Eq. (5.16).

$$\begin{bmatrix} [\underline{I}_K] \\ [\underline{U}_K] \end{bmatrix} = [\underline{H}_Y] \cdot \begin{bmatrix} [\underline{U}_U] \\ [\underline{I}_U] \end{bmatrix} \tag{5.16}$$

Where, the unknown voltage vector [$\underline{U}_U$] and the unknown current vector [$\underline{I}_U$] are arranged to the right hand side or input side. In order to derive the admittance hybrid matrix, the sorted admittance matrix is once more taken into account. In this case, the second row of Eq. (5.5) is firstly taken into account, it gives

$$[\underline{I}_U] = [\underline{Y}_{BA}][\underline{U}_U] + [\underline{Y}_{BB}][\underline{U}_K] \tag{5.17}$$

To obtain the second row of admittance hybrid matrix as in Eq. (5.16), the Eq. (5.17) is subsequently rearranged. The known voltage vector [$\underline{U}_K$] is moved to the left side, it can be obtained as in Eq. (5.18).

$$[\underline{U}_K] = -[\underline{Y}_{BB}]^{-1}[\underline{Y}_{BA}][\underline{U}_U] + [\underline{Y}_{BB}]^{-1}[\underline{I}_U] \tag{5.18}$$

Afterwards, the first row of the sorted admittance matrix in Eq. (5.5) is taken into account. It can be written as

$$[\underline{I}_K] = [\underline{Y}_{AA}][\underline{U}_U] + [\underline{Y}_{AB}][\underline{U}_K] \tag{5.19}$$

In order to complete the first row of the admittance hybrid equation, the known voltage vector [$\underline{U}_K$] in Eq. (5.19) has to be eliminated. It must be substituted by Eq. (5.18). The result is given in Eq. (5.20).

$$[\underline{I}_K] = \left\{ [\underline{Y}_{AA}] - [\underline{Y}_{AB}][\underline{Y}_{BB}]^{-1}[\underline{Y}_{BA}] \right\} \cdot [\underline{U}_U] + [\underline{Y}_{AB}][\underline{Y}_{BB}]^{-1}[\underline{I}_U] \tag{5.20}$$

Joining Eq. (5.20) and Eq. (5.18) in matrix form, respectively. Consequently, the admittance hybrid matrix [$\underline{H}_Y$] can be achieved as in Eq. (5.21).

$$\begin{bmatrix} [\underline{I}_K] \\ [\underline{U}_K] \end{bmatrix} = \begin{bmatrix} [\underline{Y}_{AA}] - [\underline{Y}_{AB}][\underline{Y}_{BB}]^{-1}[\underline{Y}_{BA}] & [\underline{Y}_{AB}][\underline{Y}_{BB}]^{-1} \\ -[\underline{Y}_{BB}]^{-1}[\underline{Y}_{BA}] & [\underline{Y}_{BB}]^{-1} \end{bmatrix} \cdot \begin{bmatrix} [\underline{U}_U] \\ [\underline{I}_U] \end{bmatrix} \tag{5.21}$$

As a result, the target equation of admittance hybrid matrix is stated in Eq. (5.21). Clearly, the first matrix element is described by the admittance form.

In fact, both impedance- and admittance hybrid matrices are the inversion of each other for every symmetrical network and also asymmetrical network. Unfortunately, it has to be mentioned that both hybrid matrixes are utilized in a different way of cluster analysis algorithm. To figure out the different usage of both hybrid matrix types related to an analysis algorithm, it is further in detail in Chapter 6.

5.4 Advantages of Hybrid Calculation Method for Cluster Systems Analysis

As the cluster system network and control application lead the target of cluster management and operation in a decoupling approach as clarified in section 5.1. It rolls out directly the cluster analysis strategy in decoupling way to fulfill the target of cluster operation. To achieve the decoupling cluster network analysis, the interaction behavior from other interconnected clusters must be transferred and integrated into each single area analysis, which the interaction behavior can be represented by power system state variable, interconnected clusters bus voltage. Hence, the cluster analysis method must solve the power flow study, in which the examined network is contained more than one voltage source. To emphasize decoupling cluster analysis strategy in detail, a simple three interconnected clusters network is portrayed in Fig. 5.6. For example, the voltage of bus *i* from cluster1 and the voltage of bus *j* from cluster3 must be sent to cluster2. Afterwards, the cluster2 can be executed the load flow analysis based on area itself. It is noteworthy that the linkage to cluster1 ($\underline{Z}_{ii}$) and the linkage to cluster1 ($\underline{Z}_{jj}$) must be added into cluster2 network model in order to keep physical character of power flow between clusters.

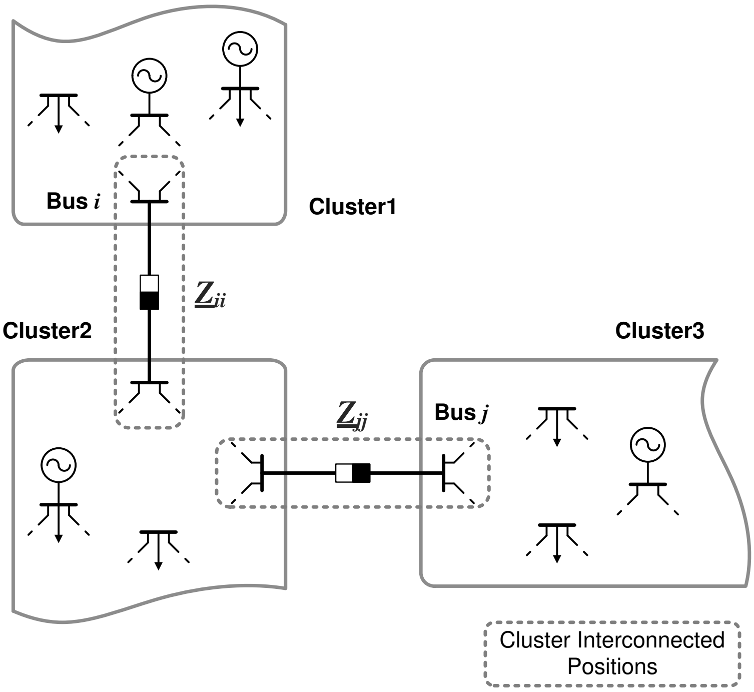


Fig. 5.6: A simple three interconnected clusters network

Since the conventional load flow methods cannot fulfill the requirements of cluster analysis strategy as mentioned in section 5.2, the hybrid calculation technique is subsequently considered. The hybrid technique gives an opportunity to solve load flow solution, where the power network consists of mixing of voltage sources and current sources. It can be implied that the describing of interconnected clusters can be accomplished based on the voltage sources part. As a result, it executes the decoupling cluster analysis strategy. Moreover, the current sources part of hybrid method provides huge advantages regarding the supporting of intelligent source, which is commonly described by current source. According to those advantages, the hybrid calculation technique is promoted as a key calculation method for cluster systems analysis.

Applying hybrid calculation method, the analysis of the introduced three interconnected clusters network in Fig. 5.6 is resulted in decoupling way as shown in Fig. 5.7. Noticeably, the interconnected clusters are decoupled in order to perform load flow analysis based on area itself. Information exchanging positions between three clusters are highlighted to emphasize once more that the information at the interconnected buses are only exchanged. This is not only a benefit in cluster analysis, but also in data management.

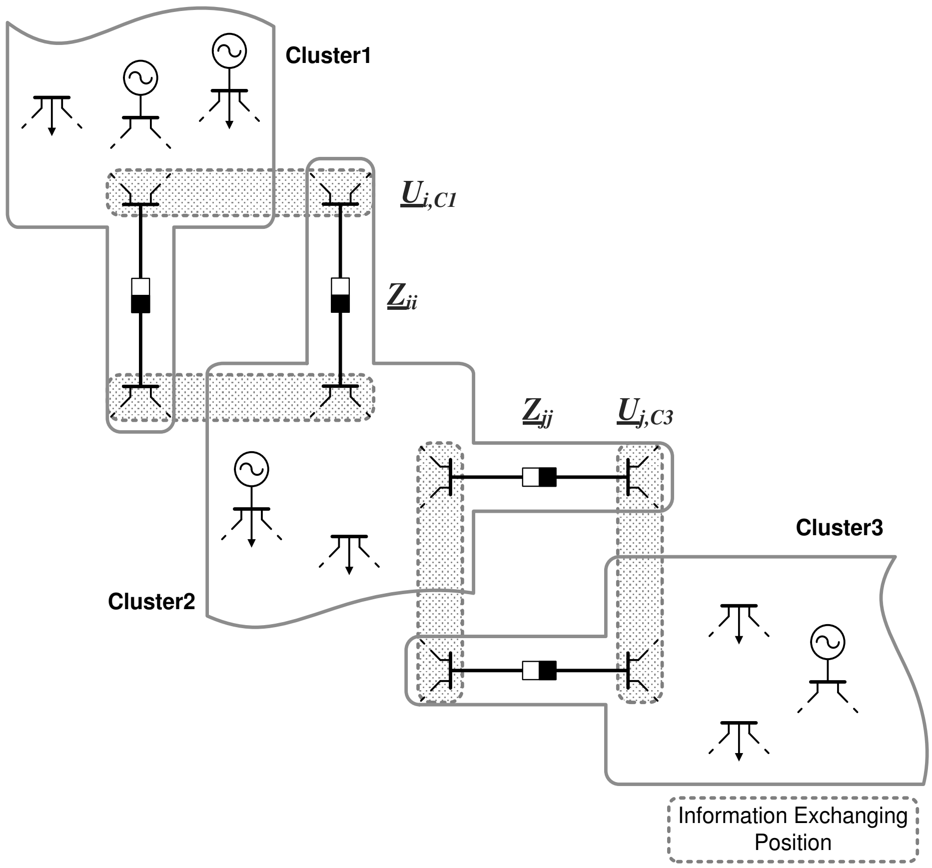


Fig. 5.7: Decoupling analysis approach of interconnected clusters

To explain the decoupling load flow analysis in a mathematic way, the cluster2 is selected for an explanation. All generator units and loads in cluster2 are assumed to operate as current sources. The interconnected bus voltage $\underline{U}_{i,c1}$ and $\underline{U}_{i,c3}$ are transferred to cluster2 in order to describe behavior of cluster1 and cluster3, respectively. Under this assumption, the decoupling hybrid load flow equation of cluster2 can be obtained in Eq. (5.22).

$$\begin{bmatrix} \underline{I}_{1,C2} \\ \vdots \\ \underline{I}_{n,C2} \\ \underline{U}_{i,C1} \\ \underline{U}_{j,C3} \end{bmatrix} = \begin{bmatrix} \underline{Y}_{11,h} & \cdots & \underline{Y}_{1n,h} & \underline{x}_{1i,h} & \underline{x}_{1j,h} \\ \vdots & \ddots & \vdots & \vdots & \vdots \\ \underline{Y}_{n1,h} & \cdots & \underline{Y}_{nn,h} & \underline{x}_{ni,h} & \underline{x}_{nj,h} \\ \underline{x}_{i1,h} & \cdots & \underline{x}_{in,h} & \underline{Z}_{jj,h} & \underline{Z}_{ij,h} \\ \underline{x}_{j1,h} & \cdots & \underline{x}_{jn,h} & \underline{Z}_{ji,h} & \underline{Z}_{jj,h} \end{bmatrix} \cdot \begin{bmatrix} \underline{U}_{1,C2} \\ \vdots \\ \underline{U}_{n,C2} \\ \underline{I}_{i,C1} \\ \underline{I}_{j,C3} \end{bmatrix} \tag{5.22}$$

Where n is the number of buses in the cluster2 network, and subscript h stand for hybrid value. The stated hybrid matrix is the admittance hybrid matrix. As a consequence, the general target equation of admittance hybrid matrix in Eq. (5.16) is utilized in this case. Solving load flow problem of this hybrid equation, the current iteration process is utilized. Finally, the decoupling load flow problem of cluster2 is calculated through load flow equation as written in Eq. (5.2).

Up to this point, it must be mentioned that the explanation of cluster decoupling process in Fig. 5.7 and the definition of Eq. (5.22) are a key of decoupling system analysis based on hybrid calculation method. In order to validate proposed method and strategy, the case study is given in the following section.

5.5 Verification of Decoupling Cluster Systems Analysis

Validating the decoupling cluster system analysis, the dynamic-RMS load flow simulation platform, as introduced in section 4.3.1, is taken in to account. Basically, the dynamic-RMS model is developed based on the current injection load flow method. To add the decoupling functionality, the hybrid calculation technique is integrated into the original dynamic-RMS simulation platform. Applying the hybrid technique, the voltages at any concerned decoupling position are able to exchange. As a result, the original simulation platform is improved through the decoupling analysis function.

To figure out the integration of hybrid calculation technique into dynamic-RMS simulation platform, the following three steps are pointed out for an explanation.

- Specifying decoupling position of the power systems
- Applying hybrid load flow calculation in order to decouple cluster analysis
- Decoupling dynamic-RMS simulation platform

Specifying decoupling position of the cluster power system

As the cluster system analysis is aimed to perform based on each cluster area, thus, it is initially important to point out the decoupling position. In general, the cluster interconnected positions are automatically specified as decoupling position. For example, the simple cluster system in Fig. 5.8 is introduced, which the second bus and the fifth bus are selected to decouple. Consequently, the hybrid calculation approach is applied and implemented for the representation of cluster behavior between these decoupling positions.

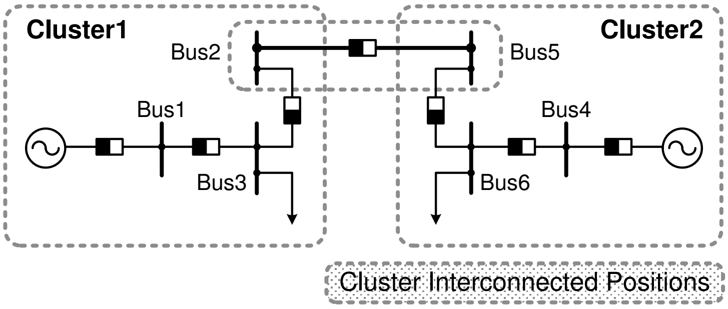


Fig. 5.8: Specifying decoupling position of the power systems

Conversely to decoupling analysis, the original dynamic-RMS simulation platform, which is basically performed under current injection method, considers this interconnected cluster systems as one power grid. Therefore, the analysis method of the original simulation platform can be referred to Eq. (5.1). As a result, the analysis equation of introduced power systems can be obtained in Eq. (5.23). Obviously, the interconnected clusters are examined under one bused admittance matrix.

$$\begin{bmatrix} \underline{U}_1 \\ \underline{U}_2 \\ \vdots \\ \underline{U}_6 \end{bmatrix} = \begin{bmatrix} \underline{Y}_{11} & \underline{Y}_{12} & \cdots & \underline{Y}_{16} \\ \underline{Y}_{21} & \underline{Y}_{22} & \cdots & \underline{Y}_{26} \\ \vdots & \vdots & \ddots & \vdots \\ \underline{Y}_{61} & \underline{Y}_{62} & \cdots & \underline{Y}_{66} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \underline{I}_1 \\ \underline{I}_2 \\ \vdots \\ \underline{I}_6 \end{bmatrix} \tag{5.23}$$

Applying hybrid load flow calculation in order to decouple cluster analysis

After figuring out the decoupling position, the introduced cluster system is decoupled as shown in Fig. 5.9, which portrays the situation where the system is decoupled into two cluster areas. As mentioned in section 5.4 about the decoupling analysis process and exchange parameter, it requires only interconnected cluster voltage to include into hybrid calculation technique. Under this assumption of hybrid calculation approach, it executes the original dynamic-RMS simulation platform into the decoupling analysis.

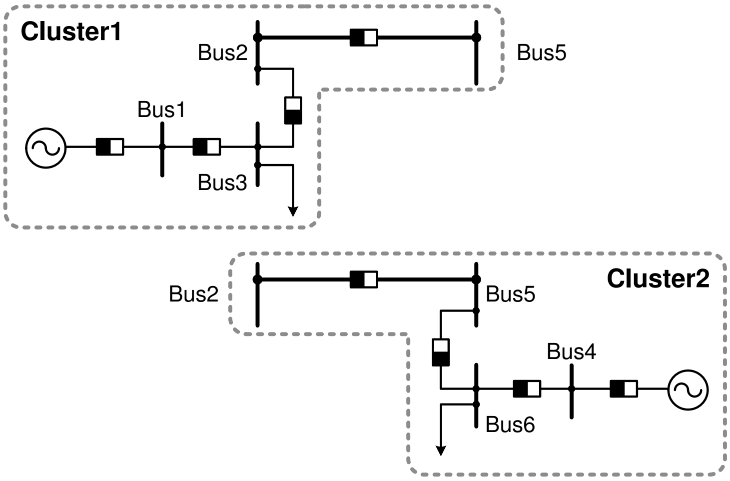


Fig. 5.9: Decoupling cluster systems process

To explain in more detail, two hybrid matrices are needed to active a decoupling load flow calculation of the present cluster system. One from the first cluster and another one from the second cluster, where the decoupled bus is set as the known voltage bus and the rest is the known current bus in hybrid calculation. For instance, the hybrid equation of the first cluster can be shown in Eq. (5.24).

$$\begin{bmatrix} \underline{U}_{1,C1} \\ \underline{U}_{2,C1} \\ \underline{U}_{3,C1} \\ \underline{I}_{5,C2} \end{bmatrix} = \begin{bmatrix} \underline{Z}_{11,h} & \underline{Z}_{12,h} & \underline{Z}_{13,h} & \underline{x}_{15,h} \\ \underline{Z}_{21,h} & \underline{Z}_{22,h} & \underline{Z}_{23,h} & \underline{x}_{25,h} \\ \underline{Z}_{31,h} & \underline{Z}_{32,h} & \underline{Z}_{33,h} & \underline{x}_{35,h} \\ \underline{x}_{51,h} & \underline{x}_{52,h} & \underline{x}_{53,h} & \underline{Y}_{55,h} \end{bmatrix} \cdot \begin{bmatrix} \underline{I}_{1,C1} \\ \underline{I}_{2,C1} \\ \underline{I}_{3,C1} \\ \underline{U}_{5,C2} \end{bmatrix} \tag{5.24}$$

According to generating model and load model of dynamic-RMS simulation platform in section 4.3.1, bus1, bus 2 and bus3 are directly described by current injection form. Meanwhile, the bus5, which represents interconnected cluster behavior, is defined by the terminal bus voltage. It must note that the hybrid equation of the second cluster is also applied in the same way. Currently, the hybrid calculation technique is applied into dynamic-RMS simulation platform, and accomplish in the term of decouple the systems analysis. Unfortunately, the load flow output dynamic-RMS platform is only mapped with the current injection platform. Therefore, the results of hybrid calculation have to be transferred to the final stage or a current injection load flow algorithm.

Decoupling dynamic-RMS simulation platform

In the final stage of decoupling dynamic-RMS simulation platform, the results of hybrid calculation are used to active current injection load flow algorithm. Considering the output of Eq. (5.24), an exchanged current between cluster1 and cluster2 can be obtained in the term of value ($\underline{I}_{5,C2}$) [4]. According to this point, it will be added back to the corresponding bus. As illustrated in Fig. 5.10, the exchanged current ($\underline{I}_{5,C2}$) is added back to the second bus in cluster1. Likely, the exchanged current ($\underline{I}_{2,C1}$), which is calculated from hybrid equation of cluster2 is added back to the fifth bus in the same way. Finally, the decoupling power system analysis based on dynamic-RMS simulation platform is successful by the calculation based on injection current method. To emphasize, Fig. 5.10 shows that two cluster are calculated separately in each cluster area.

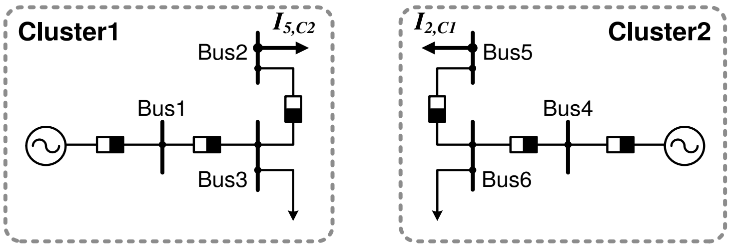


Fig. 5.10: Decoupling cluster system analysis in dynamic-RMS simulation platform

Finally, the load flow equation based current injection method can be concluded in Eq. (5.25), where the cluster1 is selected to represent.

$$\begin{bmatrix} \underline{U}_{1,C1} \\ \underline{U}_{2,C1} \\ \underline{U}_{3,C1} \end{bmatrix} = \begin{bmatrix} \underline{Y}_{11} & \underline{Y}_{12} & \underline{Y}_{13} \\ \underline{Y}_{21} & \underline{Y}_{22} & \underline{Y}_{23} \\ \underline{Y}_{31} & \underline{Y}_{32} & \underline{Y}_{33} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \underline{I}_{1,C1} \\ \underline{I}_{2,C1} + \underline{I}_{5,C2} \\ \underline{I}_{3,C1} \end{bmatrix} \tag{5.25}$$

To summarize, the hybrid calculation technique is integrated into dynamic-RMS simulation platform as an intermediate section to transfer the connected cluster behavior. The results of hybrid calculation execute the decoupling analysis of dynamic-RMS model.

Up to this point, the examined interconnected clusters system in Fig. 5.11 is set up in order to verify the proposed decoupling cluster system analysis based on hybrid calculation method. In the case study, there are two examined simulation cases as following:

- The decoupling cluster systems analysis
- The total system analysis

According to the first simulation case study, the examined system is decoupled into three clusters and the decoupling positions are shown inside dot areas. Then, the dynamic-RMS simulation platform with hybrid technique is utilized. The second case study, the same interconnected systems are examined, but it is considered as one power system. Thus, the three cluster areas from first case are considered as one grid area in this case. The original dynamic-RMS simulation platform is used to analyze the second case.

Finally, the comparative results of both case studies are used to validate the proposed decoupling cluster system analysis. It is worth to mention that the cluster control applications (horizontal- and vertical control application) are not considered in both simulation cases.

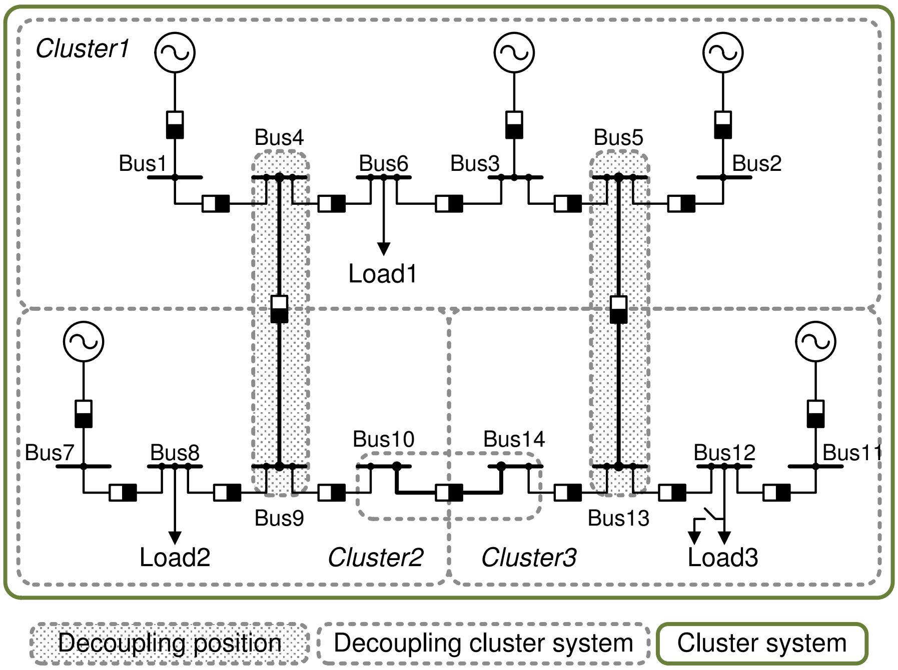


Fig. 5.11: Examined interconnected clusters system

The parameters for the test power system are described as follows; all five generator parameters are identical; rated apparent power S is 50 kVA, nominal voltage is 400 $V_{L\text{-}L}$ and nominal frequency is 50 Hz. Each bus is connected with 10 m NAYY 4×50 SE cables; R_l = 0.772 Ω/km and X_l =0.083 Ω/km. There are three loads in the examined system, whose load profiles are shown in Table 5.1. Moreover at t = 30 s, a step load is applied on the third load to observe the dynamic behavior of the examined system.

Table 5.1: Reference value of generator, inverter and load

	Load1	Load2	Load3	Step load at load3
P [pu.]	1.00	1.00	1.00	1.00
Q [pu.]	0.50	0.50	0.50	0.25

Providing the proof and the accuracy of proposed decoupling power system analysis based on hybrid method, the simulation results of both case studies are compared with each other. The comparative simulation results of selected bus (bus11) are shown in Fig. 5.12 including; active power, reactive power, terminal voltage of generator bus, and power system frequency.

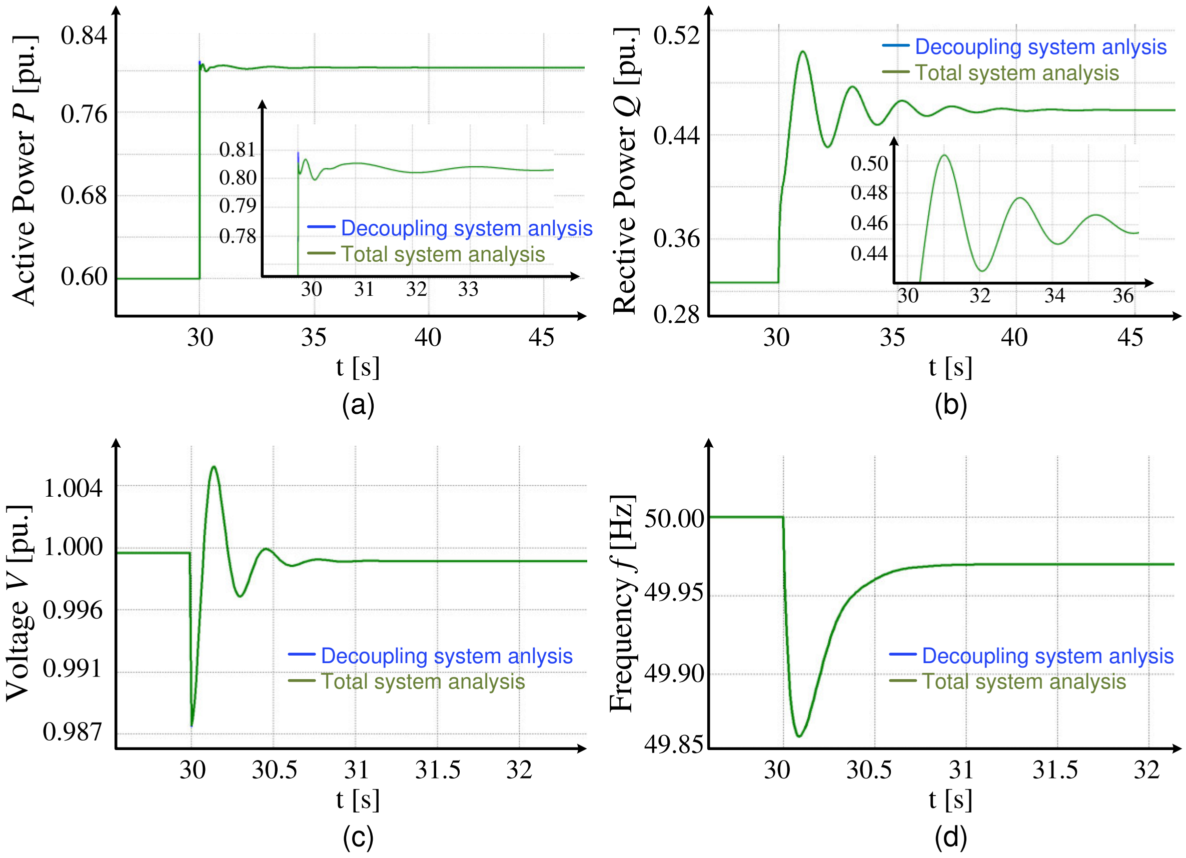


Fig. 5.12: Comparison of simulation results at bus11

Firstly, the active power result in Fig. 5.12.a is discussed. The summation of the active power load demand (3 pu.) has to be supplied by all five generators, which supply approximately 0.6 for each generator. At *t*=30s, the step load of 1 pu. is added into bus13. This added load demand is supplied by all generators as well. However, each generator supplies around 0.8 pu. Moreover, the comparative result shows the accuracy of the decoupling analysis method, the results of both cases are the same, even in the zoom window.

Secondly, the reactive power result in Fig. 5.12.b is concerned. As the sharing of reactive power is related to the bus voltage, therefore, the sharing of reactive power is not the same for each generator. Due to that reason, it cannot examine in detail like active power part. Nevertheless, it must be noted that all generators can cover the summation and the load change of reactive power load. The comparative result of the generated reactive power of both cases is the same even in dynamic phase. Furthermore, the zoom window is also the proof of the accuracy of the decoupling analysis method.

Thirdly, the comparative result of the terminal voltage of bus11 is shown in Fig. 5.12.c. The difference of the comparative result of the terminal voltage cannot be observed. Moreover, the dynamic behavior is correct due to droop function. After the step load is added to the system, the terminal voltage is drop. And after few minutes, it returns back to the proper value.

Lastly, the comparative result of the system frequency is shown in Fig. 5.12.d. The simulated system is starting with the nominal frequency at 50 Hz, and it drops after adding the step load into the system due to the droop control function. As a result, both simulation results are in the same behavior, and there is no difference.

In summary, the hybrid technique is applied into the dynamic-RMS simulation platform in order to validate the decoupling cluster system analysis strategy. In the simulation case studies, the comparative results between the decoupling analysis method and the total system analysis provide the same results. The difference cannot be observed. Hence, the accuracy of the proposed method can be assured.

5.6 Summary

To fulfill the cluster control and management operation, the proper analysis method is required. Because the cluster concept may cause in the flexible changing of the cluster system network, this consequences in a complex analysis. Therefore, the decoupling analysis approach is taken into account as a strategy for a cluster system analysis. To realize the decoupling analysis, the interaction behavior from other clusters has to be integrated into analysis based on cluster area itself. The voltage is consequently selected for the representation of the interconnected cluster behavior. Since the voltage is power systems state variable, where describes and identifies the power network character.

Finding the proper analysis method, the conventional current injection method and Newton-Raphson method are initially considered. It found that both analysis methods are unsuitable for cluster analysis strategy. The current injection method cannot describe the behavior of interconnected cluster, which is described by voltage source. The classical Newton-Raphson method can be further developed to perform the decoupling cluster system analysis. However, the power mismatch equation with the Jacobian matrix has to be updated in every iteration process. Thus, the Newton-Raphson method can cause a high computational time in power flow analysis.

Consequently, the hybrid calculation technique is further investigated. This method has ability to solve load flow problem of the network with mixing type of voltage source and current source. The representation of interconnected clusters can be directly described by voltage source part. Furthermore, the intelligent component e.g. inverter, which described by simply current source model, is supported in the part of current source. Last but not least, the hybrid calculation method provides a fast computational time, since the iteration process can be basically accomplished by simple current iteration process. Hence, the hybrid calculation technique is pointed out as the method for cluster system analysis.

To verify the concept of decoupling analysis based hybrid calculation, the dynamic-RMS load flow simulation platform is considered and modified. After applying the hybrid technique, the voltages at concerned decoupling position are able to exchange. As a result, the original simulation platform can analyze in the decoupling way. Providing the validation and showing the accuracy of proposed decoupling power system analysis based hybrid method, the studied cluster system are setup, and it is examined under the decoupling systems analysis and the total system analysis. Consequently, the comparative results of active power, reactive power, terminal voltage of generator bus, and power system frequency are investigated. It found that both simulation platforms show the same results; the difference cannot be observed. This is the proof of the decoupling analysis based on hybrid calculation

In conclusion, the success of decoupling power systems analysis is clarified the analysis of cluster system. Consequently, the decoupling cluster system analysis based on hybrid technique is promoted as one of DMS functions in order to accomplish automated cluster operation and management. Nevertheless, to evolve sustainable cluster load flow algorithm based hybrid technique, an asymmetrical condition in power network, especially in distribution network, must be taken into account. For example, the network topology in low voltage level, which may consist of multi-phase distribution topology, or single phase feed in power of DG units. The development of decoupling power systems analysis under asymmetrical grid condition executes the automated cluster control, and opens up cluster management system in distribution network. Finally, the intention to close the gap between transmission and distribution system operation with the compatibility becomes obvious. In next chapter, the cluster load flow analysis algorithm based on hybrid calculation method for asymmetrical grid condition is given in detail.

6. Cluster System Analysis Algorithm for Asymmetrical Grid Conditions

Presently, the method for cluster analysis strategy is pointed out through the hybrid calculation method, since it is able to include the behaviors of interconnected clusters systems. As a result, the cluster analysis can be done in a decoupling way. However, it must be mentioned that the recent development of cluster analysis method is described based on symmetrical conditions. To success the cluster analysis in entire power systems, there is another significant condition to concern, which is a nature of asymmetrical grid. Therefore, the main target in this chapter is the discussions and the development of asymmetrical cluster systems analysis based on hybrid method. This chapter expresses a major difference between symmetrical and asymmetrical grid conditions including the asymmetrical power systems analysis methods, which are recently widely utilized. Consequently, an asymmetrical cluster system analysis algorithm is introduced. The achievement of developed algorithm is the next step of DMS functionality in order to execute the cluster management operation.

6.1 Asymmetrical Network Conditions

In order to accomplish in the asymmetrical cluster analysis, the characters of asymmetrical network must be thoroughly taken into account due to the unbalanced or asymmetrical conditions. Considering the asymmetrical network conditions, the distribution systems are commonly concerned. The distribution systems start from the substation until end consumption unit. A major function of distribution substation is obviously to transform the medium voltage to low voltage level. To deliver the power to consumption unit, the power is typically fed via the radial feeder. This kind of network structure may consist of three phases, two phases, or single phase [136]. Therefore, the distribution systems are inherently an unbalanced network. Moreover, an earthing system is another issue of the distribution network. Since electricity consumption in our daily life may risk to fatal accident, therefore, a safety system in distribution network and house is considered. The IEC 60364-1 international standard provides three standards earthing systems TT, TN, and IT as a protection network. Further information can be found in [137]. Regarding those protection systems, a neutral cable plays an important role for detecting a fault as well as an earth leakage current. It is worth to mention that the neutral cable exists only the distribution level.

Describing any asymmetrical network, a basic description of bus admittance matrix can be used. To clarify, an example of three-phase network is given, as illustrated in Fig. 6.1. Where, a lumped parameter of three-phase cable is defined as $Z_{aa} \neq Z_{bb} \neq Z_{cc}$, and $Z_{ab} \neq Z_{bc} \neq Z_{ac}$.

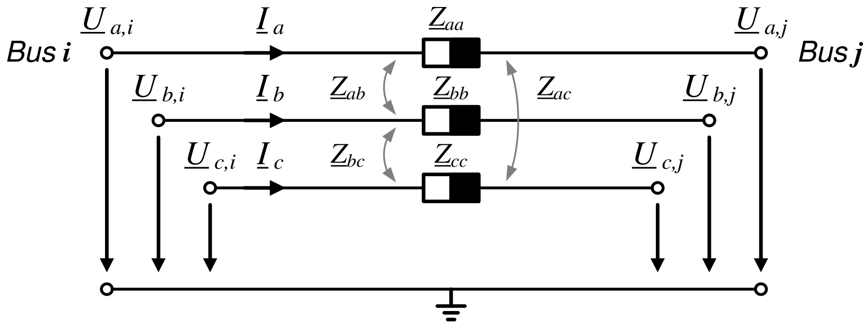


Fig. 6.1: Example of three-phase impedance network

As introduced, the network cannot be described by a symmetrical or single phase system. Therefore, the mathematic description of this three-phase cable must be described by 3×3 matrix dimension instead of 1×1, as written in Eq. (6.1).

$$\underline{Z}_{abc,ij} = \begin{bmatrix} \underline{Z}_{aa} & \underline{Z}_{ab} & \underline{Z}_{ac} \\ \underline{Z}_{ab} & \underline{Z}_{bb} & \underline{Z}_{bc} \\ \underline{Z}_{ac} & \underline{Z}_{bc} & \underline{Z}_{cc} \end{bmatrix} \tag{6.1}$$

Subsequently, the network model between bus *i* and bus *j* can be accomplished by using the simple bus admittance matrix as in Eq. (6.2).

$$\begin{bmatrix} \underline{I}_{abc,i} \\ \underline{I}_{abc,j} \end{bmatrix} = \begin{bmatrix} \underline{Y}_{abc,ij} & -\underline{Y}_{abc,ij} \\ -\underline{Y}_{abc,ij} & \underline{Y}_{abc,ij} \end{bmatrix} \begin{bmatrix} \underline{U}_{abc,i} \\ \underline{U}_{abc,j} \end{bmatrix} \tag{6.2}$$

Based on a simple explanation, it can be understood that the familiar single phase bus admittance matrix can be extended and utilized for any system network, e.g. a multi-phase topology of low voltage network. Hence, a key to success in describing power systems is a model of network elements, i.e., three-phase transformer and cable. The mathematic description of the transformer model and the cable model including neutral cable are explained in the section 9.1.

Currently, the network model by using bus admittance matrix is elucidated based on phase system. Nonetheless, the bus admittance matrix can be described in another approach, called sequence components. The sequence components technique is a powerful analytical technique for three-phase system analysis. It provides a transformation matrix (*T*) in order to convert phase system into three sequence frameworks, positive sequence (*1*), negative sequence (*2*), and zero sequence (*0*). As a result, the three-phase cable in Eq. (6.1) can be transformed in sequence frameworks through Eq. (6.3). Since sequence components technique is a very well-known method, a description and derivation of this technique are neglected for the discussion in this thesis. They can be widely found in almost of power system analysis books e.g. [138].

$$\underline{Z}_{120,ij} = \underline{T}^{-1} \cdot \underline{Z}_{abc,ij} \cdot \underline{T} \quad ; \quad \underline{T} = \begin{bmatrix} 1 & 1 & 1 \\ a^2 & a & 1 \\ a & a^2 & 1 \end{bmatrix} \tag{6.3}$$

Where T is a transformation matrix, and a is a complex factor, which equals to $e^{j120°}$. As a consequence, the three-phase cable in Eq. (6.1) results in sequence frameworks as

$$\underline{Z}_{120,ij} = \begin{bmatrix} \underline{Z}_{11} & \underline{Z}_{12} & \underline{Z}_{10} \\ \underline{Z}_{21} & \underline{Z}_{22} & \underline{Z}_{20} \\ \underline{Z}_{01} & \underline{Z}_{02} & \underline{Z}_{00} \end{bmatrix} \tag{6.4}$$

Thus, the network model between bus i and bus j or bus admittance matrix based sequence components can be obtained in Eq. (6.5).

$$\begin{bmatrix} \underline{I}_{120,i} \\ \underline{I}_{120,j} \end{bmatrix} = \begin{bmatrix} \underline{Y}_{120,ij} & -\underline{Y}_{120,ij} \\ -\underline{Y}_{120,ij} & \underline{Y}_{120,ij} \end{bmatrix} \begin{bmatrix} \underline{U}_{120,i} \\ \underline{U}_{120,j} \end{bmatrix} \tag{6.5}$$

If the network in Fig. 6.1 is considered as a symmetrical network ($Z_{aa} = Z_{bb} = Z_{cc}$, and $Z_{ab} = Z_{bc} = Z_{ac}$), the sequence components technique results the description of three-phase cable in a decoupled way, where the matrix parameters exist only on a diagonal position as portrayed in Eq. (6.6)

$$\underline{Z}_{120,ij} = \begin{bmatrix} \underline{Z}_{11} & 0 & 0 \\ 0 & \underline{Z}_{22} & 0 \\ 0 & 0 & \underline{Z}_{00} \end{bmatrix} \tag{6.6}$$

Consequently, the bus admittance matrix based sequence components in Eq. (6.5) can be written in a decoupled way in Eq. (6.7).

$$\begin{bmatrix} \underline{I}_{1,i} \\ \underline{I}_{1,i} \end{bmatrix} = \begin{bmatrix} \underline{Y}_{11} & -\underline{Y}_{11} \\ -\underline{Y}_{11} & \underline{Y}_{11} \end{bmatrix} \begin{bmatrix} \underline{U}_{1,i} \\ \underline{U}_{1,j} \end{bmatrix}; \begin{bmatrix} \underline{I}_{2,i} \\ \underline{I}_{2,i} \end{bmatrix} = \begin{bmatrix} \underline{Y}_{22} & -\underline{Y}_{22} \\ -\underline{Y}_{22} & \underline{Y}_{22} \end{bmatrix} \begin{bmatrix} \underline{U}_{2,i} \\ \underline{U}_{2,j} \end{bmatrix}; \begin{bmatrix} \underline{I}_{0,i} \\ \underline{I}_{0,j} \end{bmatrix} = \begin{bmatrix} \underline{Y}_{00} & -\underline{Y}_{00} \\ -\underline{Y}_{00} & \underline{Y}_{00} \end{bmatrix} \begin{bmatrix} \underline{U}_{0,i} \\ \underline{U}_{0,j} \end{bmatrix} \tag{6.7}$$

This is the great utility of symmetrical components for every symmetrical network element. Each symmetrical framework is independent from each other. It means that the decoupled network is able to analyze in a parallel process. Moreover, it can be observed that the matrix dimension is reduced by factor of three, e.g. from 6×6 in Eq. (6.5) to 2×2 Eq. (6.7). Therefore, it also results in fast computational process.

Up to this point, the bus admittance matrix of any system network or asymmetrical network is able to describe based on either the phase system or the symmetrical components. To figure out the advantages and the disadvantages of both approaches, it must have a look on its usage in developed load flow algorithm. This is pointed next in section 6.4 and 6.5. As the proposed algorithm is target to evolve based on hybrid calculation technique. It must be stated that the preparation process and the calculation of hybrid matrix can be done by the same process as mentioned in section 5.3 for asymmetrical bus admittance matrix in both phase system bus admittance matrix and sequence components. This is because the network is basically described with linearity property. Hence, the hybrid calculation technique can be directly applied for the asymmetrical system analysis.

6.2 Asymmetrical Bus Types Specifications

To solve a power flow problem, a number of unknown quantities must agree with a number of available equations. In general practice, the classification of bus type has to be determined in order to identify the given values including its specified quantities. Regarding the conventional analysis, the bus types can be classified into three types: slack bus, voltage controlled bus, and load bus. However, the proposed cluster system analysis introduces a new approach of load flow study. Therefore, it is noteworthy to discuss how the bus type plays roles in the interconnected clusters system, and also how it is different from the conventional analysis.

The bus type specification for cluster system analysis and asymmetrical condition is classified along with the description of the conventional types as follow:

- Slack bus and imported interconnected clusters voltage bus
- Voltage controlled bus and distribution generation bus
- Load bus and generation bus

6.2.1 Slack Bus and Imported Interconnected Clusters Voltage Bus

Originally in conventional analysis, the slack bus is defined as a constant voltage bus. A voltage angle of this bus type is served as the reference angle of other buses. To figure out its specification in three-phase systems analysis, an equivalent three-phase model of ideal voltage source is illustrated in Fig. 6.2.a. In an ideal case of slack bus, a generated voltage of voltage source ($\underline{V}_p$) is directly equal to a terminal bus voltage ($\underline{U}$).

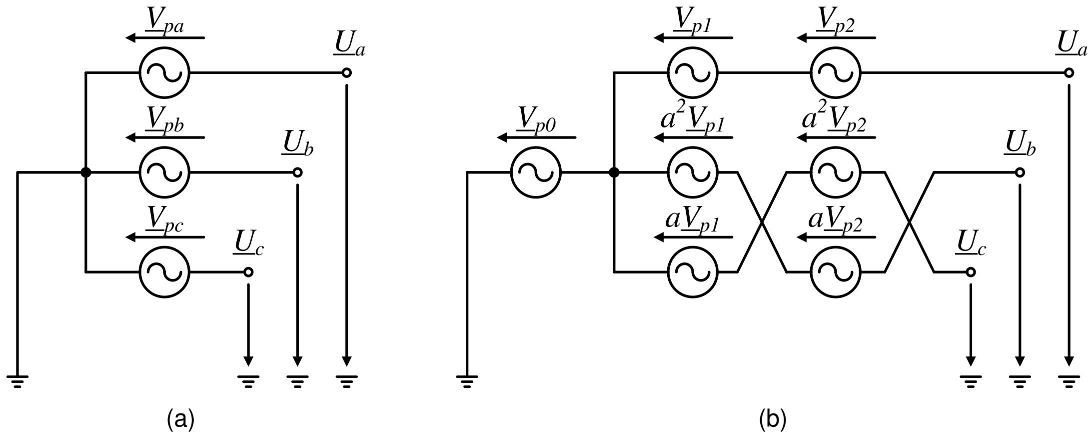


Fig. 6.2: Equivalent three-phase model of ideal voltage source [8]

Considering a sequence components voltage source model, the phase system voltage source is converted to sequence components framework by using the transform matrix ($\underline{T}$) in Eq. (6.8). Subsequently, the sequence components voltage source model is obtained in Fig. 6.2.b.

$$\underline{V}_{p,abc} = \underline{T} \cdot \underline{V}_{p,120} \; ; \; \begin{aligned} \underline{V}_{pa} &= \underline{V}_{p1} + \underline{V}_{p2} + \underline{V}_{p0} \\ \underline{V}_{pb} &= a^2\underline{V}_{p1} + a\underline{V}_{p2} + \underline{V}_{p0} \\ \underline{V}_{pc} &= a\underline{V}_{p1} + a^2\underline{V}_{p2} + \underline{V}_{p0} \end{aligned} \tag{6.8}$$

In an ideal symmetrical case, the slack bus is described by an identical voltage amplitude of every phase, and a reference voltage angle of phase *a* is set to one value, where -120° and 120° phase shift are set to phase *b* and *c*, respectively. According to those symmetrical facts, the voltage source can be decoupled into positive, negative, and zero sequences. Thus, a positive sequence of generated voltage ($\underline{V}_{p1}$) is equal to generated voltage ($\underline{V}_{pa}$); the negative and zero sequence generated voltage become zero. An equivalent model of symmetrical voltage source based sequence frameworks is depicted in Fig. 6.3.

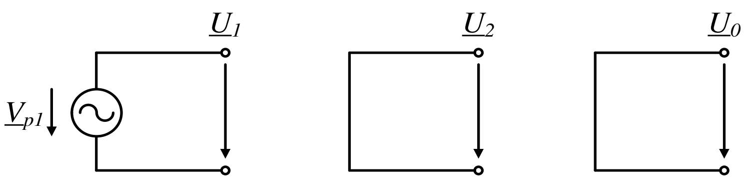


Fig. 6.3: Sequence components equivalent model of symmetrical voltage source

Currently, the specifications of slack bus is mentioned and described based on the conventional study; those are able to be transferred and also utilized in the cluster system analysis. Nevertheless, the cluster analysis strategy is aimed to perform based on the cluster area itself, where the interconnected clusters voltages must be included in analysis in order to represent the interaction between clusters. According to this fact, the interconnected clusters voltages or rather an imported voltages result in the new art of slack bus. It can be specified not only the traditional symmetrical voltage but also the asymmetrical voltage. Regarding the asymmetrical voltage source, it can be directly understood that the specification is opposite to symmetrical case. Thus, the asymmetrical voltage source model can be clarified in Fig. 6.4. For the asymmetrical voltage source, the negative and zero sequence voltage are not equal to zero at slack bus.

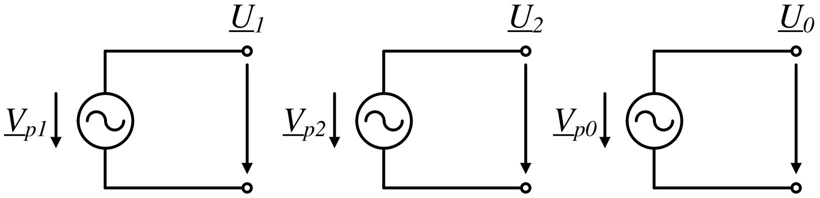


Fig. 6.4: Sequence components equivalent model of asymmetrical voltage source

Concerning imported interconnected clusters voltage bus, it can be furthermore resulted in more than one imported interconnected clusters voltages for a single cluster analysis. This is a different definition of slack bus between the conventional load flow study and the cluster system analysis.

6.2.2 Voltage Controlled Bus and Distribution Generation Bus

Traditionally, a voltage controlled bus or *PU* bus is one art of generator buses, which their injected three-phase active power and voltage magnitude are constant to their specifications. Fig. 6.5 shows an equivalent three-phase model of generator. It is noticeable that it represents in the same way as an ideal voltage source, but the internal impedance is concerned for generator model. Moreover, the generator model is can be considered as a DG unit bus, since it is mostly described as a swing generator [145].

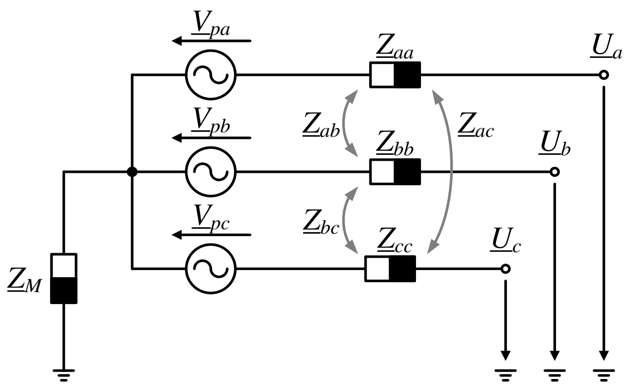


Fig. 6.5: Equivalent three-phase model of ideal generator

To figure out the specification and model of voltage controlled bus, a sequence components equivalent model of symmetrical generator in Fig. 6.6 is introduced. In conventional symmetrical system analysis, a voltage magnitude of voltage controlled bus can be only fixed to the positive voltage magnitude [146]. Meanwhile, the negative and zero sequence voltages are equal to zero. It can be implied directly that the active power injection is related to the positive sequence.

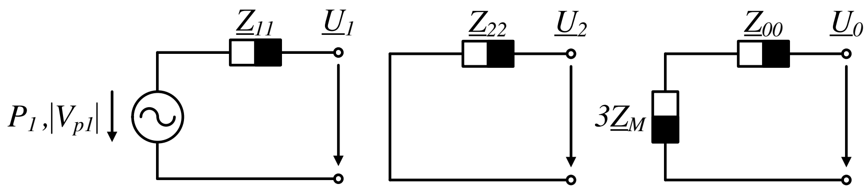


Fig. 6.6: Sequence components equivalent model of symmetrical generator [145]

The specification of voltage controlled bus is summarized in Eq. (6.9). The magnitude of positive voltage ($|V_{p1}|$) is fixed to a specified voltage (V_{spec}), and the positive active power is equal to one-third of the expected value. This definition of voltage controlled bus can be transferred to the operation of DG unit [139].

$$\begin{aligned} \left|V_{p1}\right| &= V_{spec} \\ P_1 &= \frac{P_{spec}}{3} \end{aligned} \tag{6.9}$$

According to the operation of DG unit, it cannot deliver any reactive power for any controlled voltage specification. Therefore, a limitation of reactive power has to be concerned in the model. The three-phase summation of reactive power is observed to check if it is in the boundary condition as shown in Eq. (6.10). When the reactive power has reached either maximum or minimum boundary condition, the operation of voltage controlled is automatically changed and functioned as *PQ* injection unit [145].

$$Q_{sum,\min} \le Q_{sum} \le Q_{sum,\max} \tag{6.10}$$

Conversely to the symmetrical case, the development of power electronic device, named inverter, defines the new specification of voltage controlled bus. The inverter, which is a grid interface of DG unit, is able to operate under the asymmetrical condition. Comparing with the inverter feeding modes, which are discussed in section 4.2.1, it is found that the asymmetrical voltage controlled bus is related to the operation of asymmetrical grid forming mode.

Regarding the control schema of asymmetrical grid forming mode in [110], [111] and [112], it results the specification of asymmetrical voltage controlled bus as in Fig. 6.7. Each sequence framework can set the target voltage and injection active power individually.

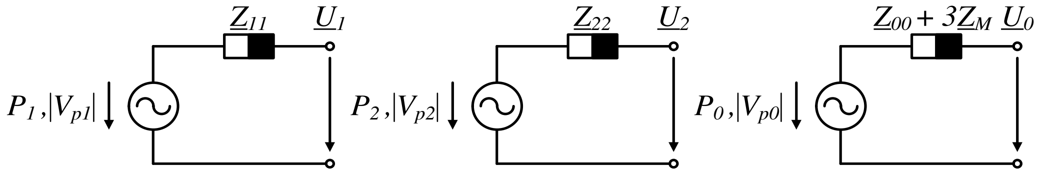


Fig. 6.7: Sequence components equivalent model of asymmetrical generator

6.2.3 Load Bus and Generation Bus

In asymmetrical three-phase load flow study, a load bus can be considered as either a three-phase balanced load or an unbalanced load, whose configuration can be a star connection or delta connection. Moreover, it can be also defined as a single-phase or two-phase load. The load bus is commonly modeled in three types, a constant power (*PQ*) load, a constant current load (*I*), and a constant impedance load (*Z*). Conversely to the load bus, a description and specification of power generation bus can be easily understood in the same way as the load bus with an opposite direction i.e. a negative sign. To clarify three types of load and generation bus model, the explanation is stated as following.

Constant power type

Normally in power flow study, a constant power (*PQ)* bus type is described by a spot, which can be functioned as a load power bus or a generation power bus. The specification of *PQ* bus is needed to concern on load circuit [140], star point to earth, star point to neutral, or delta connection, as illustrated in Fig. 6.8. The constant power load can be concerned as a load profile of the consumption unit. On the other hand, the constant power generation can be referred to the operation of grid supporting mode inverter in section 4.2.1. In load flow study, the load bus and the generation bus are identified by mathematic signs; i.e. a plus sign is for load, and minus sign is for generation.

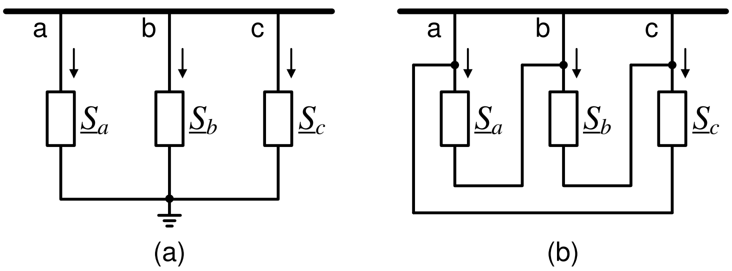


Fig. 6.8: A model of constant power bus type

Considering the hybrid calculation process, the *PQ* bus is classified in the part of current source. This means that it has to be converted to current injection form. To do that the power equation in Eq. (5.2) is taken into account. As a consequence, the injected current can be obtained as in Eq. (6.11), where *i* is bus number. Finally, the constant *PQ* bus is accomplished though a current iteration process in load flow algorithm.

$$\underline{I}_i = \left(\frac{P_i + jQ_i}{\underline{U}_i} \right)^* \tag{6.11}$$

Constant current type

The constant current type is a very power full type for describing an intelligent power systems device e.g. inverter, which can be operated as a sink or source mode. Applying constant current bus type in hybrid load flow calculation, it is matched perfectly in the part of current source. Fig. 6.9 shows a model of constant current bus type, which can be configured as star or delta connection.

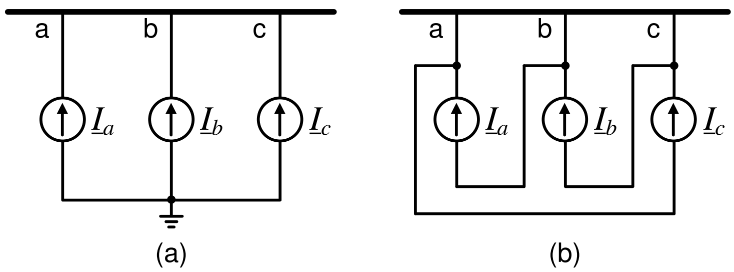


Fig. 6.9: A model of constant current bus type

If the current source model is configured by star connection, as shown in Fig. 6.9.a, it is able to inject the current into the bus directly. On the other hand, for the delta configuration as illustrated in Fig. 6.9.b, the current source must be converted into the form of phase current or star connection, as given in Eq. (6.12), where a subscript *ph* is stated for phase form.

$$\begin{aligned} \underline{I}_{a,ph} &= \underline{I}_a - \underline{I}_c \\ \underline{I}_{b,ph} &= \underline{I}_b - \underline{I}_a \\ \underline{I}_{c,ph} &= \underline{I}_c - \underline{I}_b \end{aligned} \tag{6.12}$$

Constant impedance type

Lastly, a constant impedance bus type is discussed. Since the impedance bus depends on the terminal bus voltage, the impedance has to be integrated into the bus admittance matrix as a part of network directly in order to solve the load flow problem. To do that, the load configuration must be taken into account. Fig. 6.10 shows two models of constant impedance bus type, which are star connection and delta connection, respectively.

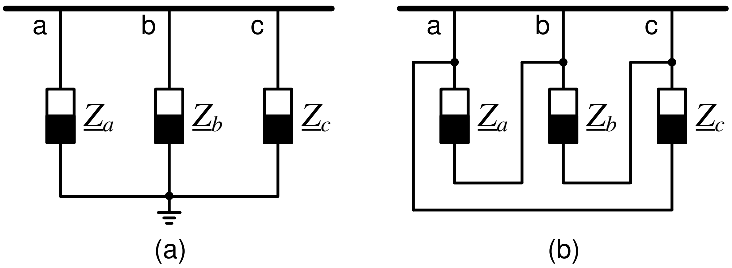


Fig. 6.10: A model of constant impedance bus type

If the impedance bus type is a star connection, it can be simply integrated into bus admittance matrix in the same way as shunt impedance. In contrast, the impedance with delta configuration cannot directly be added into bus admittance matrix. Consequently, it has to be converted to star connection form by using the relation in Eq. (6.13).

$$\underline{Z}_Y = \frac{\underline{Z}'\underline{Z}''}{\sum \underline{Z}_\Delta} \tag{6.13}$$

Where, $\underline{Z}_Y$ is the impedance of the star connection at a bus terminal node. $\underline{Z}'$ and $\underline{Z}''$ are impedance of an adjacent node in the delta connection.

In summarization, all three presented load bus or generation bus type can be configured as balance or unbalanced three-phase, two-phase, or single-phase system. Furthermore, it can be transformed to analyze in symmetrical frameworks. Among three bus types – slack bus, voltage controlled bus, and load bus – the most effect from cluster systems analysis strategy is on the slack bus type. The new art of slack bus is newly defined through the imported interconnected clusters voltage. As all types of bus are discussed, this clarifies how to organize the known voltage vector and the known current vector in hybrid calculation approach. In the next section, an overview of the most widely used methods including the requirements is briefly discussed.

6.3 Conventional Asymmetrical Load Flow Analysis Methods

Before having a look on the proposed cluster analysis algorithm, this section delivers an overview of conventional asymmetrical load flow analysis methods including the requirements of each method. The asymmetrical network conditions in section 6.1 are also concerned, since it leads to a different technique in analysis. Lastly, those all mentioned issues become a guide line for the development of asymmetrical cluster system analysis based on hybrid calculation method.

As mentioned in section 6.1 that the distribution systems are inherently concerned as the asymmetrical system due to network topology itself. Furthermore, the recent distributed network grows with penetration of the DG units. This can cause an asymmetrical problem due to the power injection, e.g. single feed in of home PV systems. Thus, it is clear that the distributed network can no longer considered as the symmetrical system. Traditionally, the distribution network is mostly structured and modeled as small radial feeder. According to this assumption, the simple power flow methods, e.g. voltage drop approach or ladder technique [136], can be utilized to solve the power flow problem.

However, when the network cannot be considered as the radial feeder, a classical Newton-Raphson analysis method is one opportunity to calculate asymmetrical power flow problem. Since the load and generation power mismatch equation can be individually defined per phase, this method can solve the unbalanced three-phase system. According to this fact, the classical Newton-Raphson method supports the power systems analysis in a full range of network description. To elucidate this application in detail, an asymmetrical Newton-Raphson load flow analysis algorithm in Fig. 6.11, [142], is introduced. Comparing this algorithm flow chart with the symmetrical one portrayed in section 5.2.2, it is obvious that an algorithm process is the same, but the target variables are extended for the three-phase system analysis. The proof of the Newton-Raphson method in asymmetrical analysis can be found in [141] and [142]. Obviously, the advantage of this method is that is requires less iteration steps for convergent condition. However, it must be noted that it takes long computational time due to the creation of updated Jacobi matrix in each iteration process, and the processing of large data set.

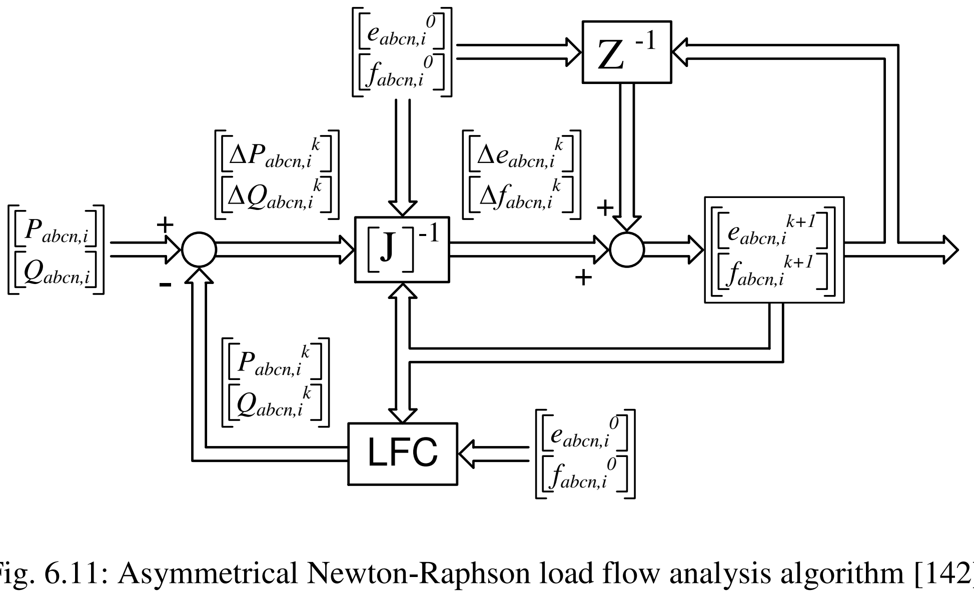


Fig. 6.11: Asymmetrical Newton-Raphson load flow analysis algorithm [142]

To reduce the complexity and the computational time of the Newton-Raphson method, the sequence components approach is considered for three-phase system analysis. This approach provides a great advantage for three-phase power systems analysis, since it can transform the three-phase system into sequence systems, i.e. positive, negative and zero sequences, and these sequences are decoupled from each other and able to calculate in a parallel process. Hence, many analysis methods are developed based on the symmetrical component; example of sequence analysis methods are detailed in [143], [144], [145], and [146]. Regarding a decoupling sequence frameworks, it is free to select the calculation technique for each sequence framework. According to a convergent performance, the Newton-Raphson approach is mostly applied in the calculation of positive sequence, [143] and [144], because the nature of power systems is normally dominated by positive sequence. On the other hand, the simple current iteration process is applied in the negative- and zero sequence. Nevertheless, the current iteration method is also able to execute in positive sequence.

Up to this point, it seems that the sequence components approach offers a simple way to model and analyze three-phase system. But its algorithm must be clarified how to deal with a non-three phases network section as well as an asymmetrical condition [147]. Moreover, as the operation of distribution networks might be faced with unbalanced configuration, a neutral to earth voltage (NEV) is subsequently necessary to investigate and observe because it is an index for power quality and safety problems. Generally, the neutral wire in three-phase power flow study is merged into the phase system through Kron's reduction process [136] under an assumption that the cable has multi-grounded and the neutral wire is also grounded, so the neutral voltage is equal to zero. This is a limitation of the asymmetrical system analysis based on sequence components technique.

Concerning the neutral cable, its analysis must be done in full network description. For example, the network description of the three-phase system with neutral cable hast to be described by 4×4 bus admittance matrix dimension. Thus, it can be implied that the calculation of neutral value, e.g. NEV, can be accomplished only by the Newton-Raphson method or the current iteration method, as found in [148], [149], and [150].

Based on the recent discussion, it clarifies a guide line for the development of asymmetrical cluster system analysis. As the hybrid calculation technique is selected and utilized in cluster analysis, the presented asymmetrical analysis method must be applied in hybrid calculation. The sequence components approach is firstly selected to match with hybrid calculation because it offers an opportunity to decouple three-phase system in to three calculation frameworks. This leads to set an algorithm to parallel calculation process. This huge advantage must not be disregarded, even though the sequence components approach cannot solve the problem of neutral cable. Subsequently, the hybrid analysis algorithm with full range of network description is also evolved. It supports the analysis of three-phase system with neutral cable, namely three-phase four-wire system. Both proposed hybrid calculation load flow algorithms can be freely selected based on network topology. For example, the cluster in medium voltage level can simply use the sequence hybrid calculation method for cluster system analysis. On the other hand, the cluster in low voltage level selects the algorithm of three-phase four-wire hybrid calculation due to the existing of neutral cable in low voltage network. However, the cluster in low voltage level can also utilize the sequence hybrid calculation method, if the neutral voltage and neutral current is neglected.

Therefore, the cluster analysis method for asymmetrical grid condition is introduced into two methods with difference analysis purpose. The sequence hybrid calculation method is used in general three-phase system. The three-phase four-wire hybrid calculation method is especially evolved for the investigation of neutral cable. Nevertheless, it is noteworthy to mention that the three-phase four-wire hybrid method can be used in general three-phase system analysis as well, but it may take longer computational time. In the following section, both hybrid analysis algorithms for asymmetrical grid are elucidated.

6.4 Asymmetrical Sequence Hybrid Load Flow Calculation Method for Three-Phase Cluster System

As mentioned that the combination between sequence components and hybrid load flow calculation is one proposed solution for the asymmetrical cluster analysis. The sequence components technique executes the simplification of a power network in three separated frameworks. As a consequence, it can decrease the computational time in three-phase power systems analysis. Unfortunately, the sequence technique is originally developed for the transmission network, which has the character as the symmetrical network. Therefore, how to utilize the symmetrical components technique for the asymmetrical network or non-three phase power network needs to be clarified before applying and implementing. To explain this problem, an asymmetrical cable model in Fig. 6.12 is concerned.

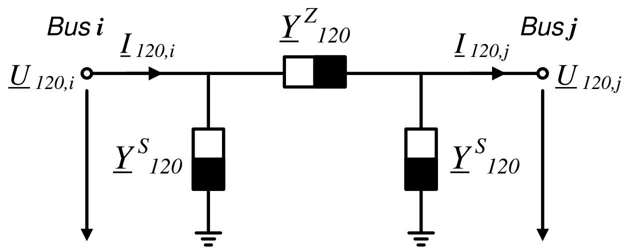


Fig. 6.12: Sequence component π-equivalent model of asymmetrical cable

A simple example of asymmetrical network is described by two-bus system, in which the buses are connected with untranspose power cable. Fig. 6.12 shows the simple π-equivalent circuit of asymmetrical three-phase power cable based on sequence components, where $\underline{Y}^Z$ is cable admittance, $\underline{Y}^S$ is shunt admittance. According to the equivalent model, the cable model is connected with bus i and bus j. Thus, the two-bus network can be described by the bus admittance matrix with sequence components as in Eq. (6.14).

$$\begin{bmatrix} \underline{I}_{1,i} \\ \underline{I}_{2,i} \\ \underline{I}_{0,i} \\ \underline{I}_{1,j} \\ \underline{I}_{2,j} \\ \underline{I}_{0,j} \end{bmatrix} = \begin{bmatrix} \underline{Y}_{11}^Z+\underline{Y}_{11}^S & \underline{Y}_{12}^Z+\underline{Y}_{12}^S & \underline{Y}_{10}^Z+\underline{Y}_{10}^S & -\underline{Y}_{11}^Z & -\underline{Y}_{12}^Z & -\underline{Y}_{10}^Z \\ \underline{Y}_{21}^Z+\underline{Y}_{21}^S & \underline{Y}_{22}^Z+\underline{Y}_{22}^S & \underline{Y}_{20}^Z+\underline{Y}_{20}^S & -\underline{Y}_{21}^Z & -\underline{Y}_{22}^Z & -\underline{Y}_{20}^Z \\ \underline{Y}_{01}^Z+\underline{Y}_{01}^S & \underline{Y}_{02}^Z+\underline{Y}_{02}^S & \underline{Y}_{00}^Z+\underline{Y}_{00}^S & -\underline{Y}_{01}^Z & -\underline{Y}_{02}^Z & -\underline{Y}_{00}^Z \\ -\underline{Y}_{11}^Z & -\underline{Y}_{12}^Z & -\underline{Y}_{10}^Z & \underline{Y}_{11}^Z+\underline{Y}_{11}^S & \underline{Y}_{12}^Z+\underline{Y}_{12}^S & \underline{Y}_{10}^Z+\underline{Y}_{10}^S \\ -\underline{Y}_{21}^Z & -\underline{Y}_{22}^Z & -\underline{Y}_{20}^Z & \underline{Y}_{21}^Z+\underline{Y}_{21}^S & \underline{Y}_{22}^Z+\underline{Y}_{22}^S & \underline{Y}_{20}^Z+\underline{Y}_{20}^S \\ -\underline{Y}_{01}^Z & -\underline{Y}_{02}^Z & -\underline{Y}_{00}^Z & \underline{Y}_{01}^Z+\underline{Y}_{01}^S & \underline{Y}_{02}^Z+\underline{Y}_{02}^S & \underline{Y}_{00}^Z+\underline{Y}_{00}^S \end{bmatrix} \cdot \begin{bmatrix} \underline{U}_{1,i} \\ \underline{U}_{2,i} \\ \underline{U}_{0,i} \\ \underline{U}_{1,j} \\ \underline{U}_{2,j} \\ \underline{U}_{0,j} \end{bmatrix} \tag{6.14}$$

In case of the asymmetrical network, sequence components result in a full element matrix as noticed in Eq. (6.14). This limits the advantage of sequence components technique in power systems analysis because the bus admittance matrix cannot be decoupled. To keep the advantage of sequence component and to solve this issue, a compensation method is consequently developed, which is aimed to eliminate the non-diagonal elements of sequence admittance matrix or hybrid matrix, those elements can be understood as an asymmetrical element. After eliminating process, the sequence matrix of asymmetrical network can be decoupled and used as the symmetrical network system. In following subsection, the compensation technique and the sequence hybrid load flow calculation algorithm are explained.

6.4.1 Asymmetrical Element Compensation Technique

Regarding the asymmetrical cable, it is obvious that the sequence bus admittance matrix is fully placed as seen in Eq. (6.14). Due to this reason, it erases the advantage of sequence component technique in power systems analysis. Normally in case of symmetrical network, the elements in sequence bus admittance matrix are only located at main diagonal position of each 3×3 matrix as in Eq. (6.6). According to this fact, the non-diagonal elements of each 3×3 matrix can be implied as asymmetrical elements, and hence, those elements must be removed in order to execute power systems analysis based on sequence components technique in a decoupling way. This asymmetrical element elimination process is called compensation technique. To figure out this elimination process, all symmetrical elements or diagonal elements are firstly removed from bus admittance matrix in order to observe an effect of asymmetrical element.

As the diagonal elements are removed in order to figure out the compensation technique, the Eq. (6.14) can be written as in Eq. (6.15), where index c in the current vector stands for compensation.

$$\begin{bmatrix} \underline{I}_{1c,i} \\ \underline{I}_{2c,i} \\ \underline{I}_{0c,i} \\ \underline{I}_{1c,j} \\ \underline{I}_{2c,j} \\ \underline{I}_{0c,j} \end{bmatrix} = \begin{bmatrix} 0 & \underline{Y}_{12}^{Z}+\underline{Y}_{12}^{S} & \underline{Y}_{10}^{Z}+\underline{Y}_{10}^{S} & 0 & -\underline{Y}_{12}^{Z} & -\underline{Y}_{10}^{Z} \\ \underline{Y}_{21}^{Z}+\underline{Y}_{21}^{S} & 0 & \underline{Y}_{20}^{Z}+\underline{Y}_{20}^{S} & -\underline{Y}_{21}^{Z} & 0 & -\underline{Y}_{20}^{Z} \\ \underline{Y}_{01}^{Z}+\underline{Y}_{01}^{S} & \underline{Y}_{02}^{Z}+\underline{Y}_{02}^{S} & 0 & -\underline{Y}_{01}^{Z} & -\underline{Y}_{02}^{Z} & 0 \\ 0 & -\underline{Y}_{12}^{Z} & -\underline{Y}_{10}^{Z} & 0 & \underline{Y}_{12}^{Z}+\underline{Y}_{12}^{S} & \underline{Y}_{10}^{Z}+\underline{Y}_{10}^{S} \\ -\underline{Y}_{21}^{Z} & 0 & -\underline{Y}_{20}^{Z} & \underline{Y}_{21}^{Z}+\underline{Y}_{21}^{S} & 0 & \underline{Y}_{20}^{Z}+\underline{Y}_{20}^{S} \\ -\underline{Y}_{01}^{Z} & -\underline{Y}_{02}^{Z} & 0 & \underline{Y}_{01}^{Z}+\underline{Y}_{01}^{S} & \underline{Y}_{02}^{Z}+\underline{Y}_{02}^{S} & 0 \end{bmatrix} \cdot \begin{bmatrix} \underline{U}_{1,i} \\ \underline{U}_{2,i} \\ \underline{U}_{0,i} \\ \underline{U}_{1,j} \\ \underline{U}_{2,j} \\ \underline{U}_{0,j} \end{bmatrix} \quad (6.15)$$

The matrix in Eq. (6.15) is declared as a compensation matrix. Regarding Eq. (6.14), it can be noticed that the sequence bus admittance matrix can be extracted into two matrices, i.e. the compensation matrix and the decoupling matrix. Consequently, Eq. (6.14) and Eq. (6.15) can be combined and rewritten as

$$\begin{bmatrix} \underline{I}_{1,i} \\ \underline{I}_{2,i} \\ \underline{I}_{0,i} \\ \underline{I}_{1,j} \\ \underline{I}_{2,j} \\ \underline{I}_{0,j} \end{bmatrix} = \begin{bmatrix} \underline{Y}_{11}^{Z}+\underline{Y}_{11}^{S} & 0 & 0 & -\underline{Y}_{11}^{Z} & 0 & 0 \\ 0 & \underline{Y}_{22}^{Z}+\underline{Y}_{22}^{S} & 0 & 0 & -\underline{Y}_{22}^{Z} & 0 \\ 0 & 0 & \underline{Y}_{00}^{Z}+\underline{Y}_{00}^{S} & 0 & 0 & -\underline{Y}_{00}^{Z} \\ -\underline{Y}_{11}^{Z} & 0 & 0 & \underline{Y}_{11}^{Z}+\underline{Y}_{11}^{S} & 0 & 0 \\ 0 & -\underline{Y}_{22}^{Z} & 0 & 0 & \underline{Y}_{22}^{Z}+\underline{Y}_{22}^{S} & 0 \\ 0 & 0 & -\underline{Y}_{00}^{Z} & 0 & 0 & \underline{Y}_{00}^{Z}+\underline{Y}_{00}^{S} \end{bmatrix} \cdot \begin{bmatrix} \underline{U}_{1,i} \\ \underline{U}_{2,i} \\ \underline{U}_{0,i} \\ \underline{U}_{1,j} \\ \underline{U}_{2,j} \\ \underline{U}_{0,j} \end{bmatrix} + \begin{bmatrix} \underline{I}_{1c,i} \\ \underline{I}_{2c,i} \\ \underline{I}_{0c,i} \\ \underline{I}_{1c,j} \\ \underline{I}_{2c,j} \\ \underline{I}_{0c,j} \end{bmatrix} \quad (6.16)$$

According to Eq. (6.16), the matrix elements remain only in diagonal position of each 3×3 matrix. Hence, this matrix can be decoupled regarding sequence components. In order to achieve the analysis based on sequence components, the current vector of Eq. (6.15) has to be considered as a compensated current. By subtracting bus injection current vector with compensated current vector, the load flow equation of asymmetrical network can be subsequently obtained as

$$\begin{bmatrix} \underline{I}_{1,i} \\ \underline{I}_{2,i} \\ \underline{I}_{0,i} \\ \underline{I}_{1,j} \\ \underline{I}_{2,j} \\ \underline{I}_{0,j} \end{bmatrix} - \begin{bmatrix} \underline{I}_{1c,i} \\ \underline{I}_{2c,i} \\ \underline{I}_{0c,i} \\ \underline{I}_{1c,j} \\ \underline{I}_{2c,j} \\ \underline{I}_{0c,j} \end{bmatrix} = \begin{bmatrix} \underline{Y}_{11}^{Z}+\underline{Y}_{11}^{S} & 0 & 0 & -\underline{Y}_{11}^{Z} & 0 & 0 \\ 0 & \underline{Y}_{22}^{Z}+\underline{Y}_{22}^{S} & 0 & 0 & -\underline{Y}_{22}^{Z} & 0 \\ 0 & 0 & \underline{Y}_{00}^{Z}+\underline{Y}_{00}^{S} & 0 & 0 & -\underline{Y}_{00}^{Z} \\ -\underline{Y}_{11}^{Z} & 0 & 0 & \underline{Y}_{11}^{Z}+\underline{Y}_{11}^{S} & 0 & 0 \\ 0 & -\underline{Y}_{22}^{Z} & 0 & 0 & \underline{Y}_{22}^{Z}+\underline{Y}_{22}^{S} & 0 \\ 0 & 0 & -\underline{Y}_{00}^{Z} & 0 & 0 & \underline{Y}_{00}^{Z}+\underline{Y}_{00}^{S} \end{bmatrix} \cdot \begin{bmatrix} \underline{U}_{1,i} \\ \underline{U}_{2,i} \\ \underline{U}_{0,i} \\ \underline{U}_{1,j} \\ \underline{U}_{2,j} \\ \underline{U}_{0,j} \end{bmatrix} \quad (6.17)$$

Currently, the system is now completely decoupled through compensated current in Eq. (6.17). Up to this point, the sequence components technique can be used and applied for analyzing the asymmetrical network.

Applying the proposed compensation technique, the asymmetrical sequence components π-equivalent cable model also results in decoupled model. Next, having a close look on the compensated currents of positive sequence of bus i. It can be obtained from the first row of Eq. (6.15), and expressed as following

$$\underline{I}_{1c,i} = \underline{Y}_{12}^{Z}\left(\underline{U}_{2,i} - \underline{U}_{2,j}\right) + \underline{Y}_{10}^{Z}\left(\underline{U}_{0,i} - \underline{U}_{0,j}\right) + \underline{Y}_{12}^{S}\underline{U}_{2,i} + \underline{Y}_{10}^{S}\underline{U}_{0,i} \tag{6.18}$$

Rearranging the compensated currents of positive sequence of bus i related to series admittance $\underline{Y}^{Z}$ and shunt admittance $\underline{Y}^{S}$, the compensated current can be separated into two parts as in Eq. (6.19).

$$\begin{aligned} \underline{I}_{1c,ij}^{Z} &= \underline{Y}_{12}^{Z}\left(\underline{U}_{2,i} - \underline{U}_{2,j}\right) + \underline{Y}_{10}^{Z}\left(\underline{U}_{0,i} - \underline{U}_{0,j}\right) \\ \underline{I}_{1c,i}^{S} &= \underline{Y}_{12}^{S}\underline{U}_{2',i} + \underline{Y}_{10}^{S}\underline{U}_{0,i} \end{aligned} \tag{6.19}$$

On the same hand, the compensated currents of positive sequence of bus j receive the fourth row of Eq. (6.15). It results in Eq. (6.20).

$$\underline{I}_{1c,j} = \underline{Y}_{12}^{Z}\left(-\underline{U}_{2,i} + \underline{U}_{2,j}\right) + \underline{Y}_{10}^{Z}\left(-\underline{U}_{0,i} + \underline{U}_{0,j}\right) + \underline{Y}_{12}^{S}\underline{U}_{2,j} + \underline{Y}_{10}^{S}\underline{U}_{0,j} \tag{6.20}$$

Repeating the manipulating process, two compensated currents regarding series admittance $\underline{Y}^{Z}$ and shunt admittance $\underline{Y}^{S}$ of bus j are shown in Eq. (6.21), respectively.

$$\begin{aligned} \underline{I}_{1c,ij}^{Z} &= \underline{Y}_{12}^{Z}\left(-\underline{U}_{2,i} + \underline{U}_{2,j}\right) + \underline{Y}_{10}^{Z}\left(-\underline{U}_{0,i} + \underline{U}_{0,j}\right) \\ \underline{I}_{1c,j}^{S} &= \underline{Y}_{12}^{S}\underline{U}_{2,j} + \underline{Y}_{10}^{S}\underline{U}_{0,j} \end{aligned} \tag{6.21}$$

Those compensated currents of positive sequence are described by the asymmetrical element and the voltage difference of the other sequences. Considering the compensated current of bus i and j in part of series admittance $\underline{Y}^{Z}$, it can be noticed that both currents are the same, but in opposite direction. In the part of shunt admittance $\underline{Y}^{S}$, there is no relation between bus i and bus j. It is fed directly into the bus itself. Understandably, the negative- and zero sequence compensated currents can be derived in the same way.

As a consequence, the π-equivalent model of asymmetrical cable based on sequence components can be decoupled, as depicted in Fig. 6.13, where the compensated current of each sequence is described by current source.

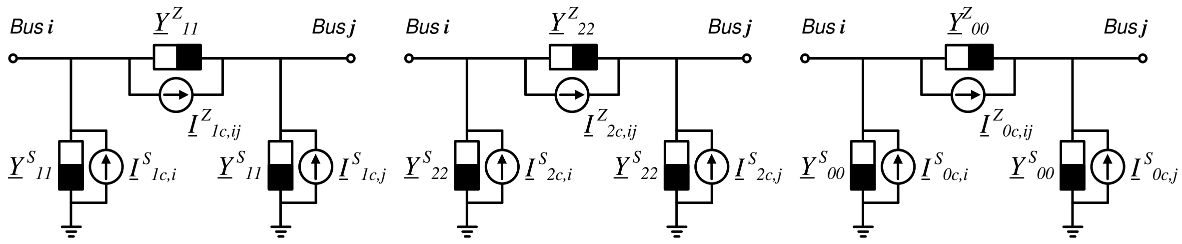


Fig. 6.13: Decoupling π-equivalent model of asymmetrical cable based on sequence components

In conclusion, as stated that the usage of sequence technique must be clarified how this technique can be applied to the asymmetrical network. The compensated current vector is considered as a solution for this issue. Every sequence bus admittance matrix can be written in the combination of the decoupling matrix and the compensation matrix. Also, the general asymmetrical load flow equation based on sequence components technique can be obtained as in Eq. (6.22). Where index *d* stands for decoupling, *c* for compensation.

$$[\underline{I}_{120}]-[\underline{I}_{120,c}]=[\underline{Y}_{120,d}]\cdot[\underline{U}_{120}] \tag{6.22}$$

The Eq. (6.22) shows that the asymmetrical load flow calculation can be achieved based on the sequence components approach. So far, the compensation technique has been introduced and explained by using the sequence bus admittance matrix. Because of the linearity property in power network description, this compensation approach can directly be applied to sequence hybrid matrix. In the following section, the sequence hybrid load flow algorithm is illustrated and discussed.

6.4.2 Sequence Hybrid Load Flow Algorithm

Since the clustering power systems concept is targeted to operate based on each cluster area, it consequently affects the analysis strategy. To support the clustering concept, the hybrid calculation method is required. It offers the opportunity to include the character of interconnected clusters, which makes decoupling analysis possible. Furthermore, the analysis method must deal with the unbalanced conditions of distribution network e.g. asymmetrical feed-in power. Therefore, the analysis based on sequence components and hybrid calculation technique is proposed to solve the asymmetrical load flow problem. Before having a look on the analysis algorithm, the hybrid matrix types, the impedance- and admittance hybrid matrices have to be examined in order to find out the compensation process. The general target equations of both matrices are shown again in Eq. (6.23).

$$\begin{bmatrix}[\underline{U}_U]\\[\underline{I}_U]\end{bmatrix}=[\underline{H}_Z]\cdot\begin{bmatrix}[\underline{I}_K]\\[\underline{U}_K]\end{bmatrix},\qquad \begin{bmatrix}[\underline{I}_K]\\[\underline{U}_K]\end{bmatrix}=[\underline{H}_Y]\cdot\begin{bmatrix}[\underline{U}_U]\\[\underline{I}_U]\end{bmatrix}\tag{6.23}$$

Considering the input vector of target hybrid equations in Eq. (6.23), the input vector of impedance hybrid equation is described by the known vectors, i.e. [$\underline{I}_K$] and [$\underline{U}_K$]. On the other hand, the input vector of admittance hybrid equation is the unknown vectors, i.e. [$\underline{U}_U$] and [$\underline{I}_U$]. This difference leads to the selection of hybrid matrix types. In the previous section, the asymmetrical element compensation technique is introduced based on the sequence buses admittance matrix. The aim of this process is to calculate the compensated current by multiplying the compensation matrix of sequence bus admittance matrix with bus voltage vector. As the bus voltage is a result of load flow study, it means that the compensated current must be updated every iteration of load flow calculation. This is a key to get the correct compensated current in asymmetrical load flow study. Since the load flow result of hybrid equation is obviously the unknown vector [$\underline{U}_U$] and [$\underline{I}_U$], therefore, the compensated vector of hybrid calculation must be extracted and calculated from the admittance hybrid matrix.

Consequently, to perform the analysis in symmetrical way, the sequence hybrid matrix must be described in the combination of decoupling matrix and compensation matrix. Thus, the target admittance hybrid equation is written as

$$\begin{bmatrix}[\underline{I}_{K120}]\\[\underline{U}_{K120}]\end{bmatrix}=[\underline{H}_{Y120,d}]\cdot\begin{bmatrix}[\underline{U}_{U120}]\\[\underline{I}_{U120}]\end{bmatrix}+[\underline{H}_{Y120,c}]\cdot\begin{bmatrix}[\underline{U}_{U120}]\\[\underline{I}_{U120}]\end{bmatrix}\tag{6.24}$$

According to compensation approach as declared in last section, the asymmetrical effect can be extracted and described by compensation term as below.

$$\begin{bmatrix}[\underline{I}_{K120,c}]\\[\underline{U}_{K120,c}]\end{bmatrix}=[\underline{H}_{Y120,c}]\cdot\begin{bmatrix}[\underline{U}_{U120}]\\[\underline{I}_{U120}]\end{bmatrix}\tag{6.25}$$

Regarding the compensation equation, the compensated vector must be subtracted from the known parameter vector. Therefore, Eq. (6.24) can be rewritten and obtained as the symmetrical system as following.

$$\begin{bmatrix}[\underline{I}_{K120}]\\[\underline{U}_{K120}]\end{bmatrix}-\begin{bmatrix}[\underline{I}_{K120,c}]\\[\underline{U}_{K120,c}]\end{bmatrix}=[\underline{H}_{Y120,d}]\cdot\begin{bmatrix}[\underline{U}_{U120}]\\[\underline{I}_{U120}]\end{bmatrix}\tag{6.26}$$

It is obvious that Eq. (6.26) is a key equation for sequence hybrid load flow algorithm. Hence, it can be decoupled into three sequence frameworks as in Eq. (6.27).

$$\begin{bmatrix}[\underline{I}_{K1}]\\[\underline{U}_{k1}]\end{bmatrix}-\begin{bmatrix}[\underline{I}_{K1,c}]\\[\underline{U}_{K1,c}]\end{bmatrix}=[\underline{H}_{Y1,d}]\cdot\begin{bmatrix}[\underline{U}_{U1}]\\[\underline{I}_{U1}]\end{bmatrix}$$

$$\begin{bmatrix}[\underline{I}_{K2}]\\[\underline{U}_{K2}]\end{bmatrix}-\begin{bmatrix}[\underline{I}_{K2,c}]\\[\underline{U}_{K2,c}]\end{bmatrix}=[\underline{H}_{Y2,d}]\cdot\begin{bmatrix}[\underline{U}_{U2}]\\[\underline{I}_{U2}]\end{bmatrix} \tag{6.27}$$

$$\begin{bmatrix}[\underline{I}_{K0}]\\[\underline{U}_{K0}]\end{bmatrix}-\begin{bmatrix}[\underline{I}_{K0,c}]\\[\underline{U}_{K0,c}]\end{bmatrix}=[\underline{H}_{Y0,d}]\cdot\begin{bmatrix}[\underline{U}_{U0}]\\[\underline{I}_{U0}]\end{bmatrix}$$

According to decoupled sequence hybrid equation together with compensation process in Eq. (6.27), the asymmetrical hybrid load flow calculation based on sequence hybrid technique becomes observable and ready for cluster system analysis. Thus, an algorithm flow chart of sequence hybrid load flow calculation is presented in Fig. 6.14.

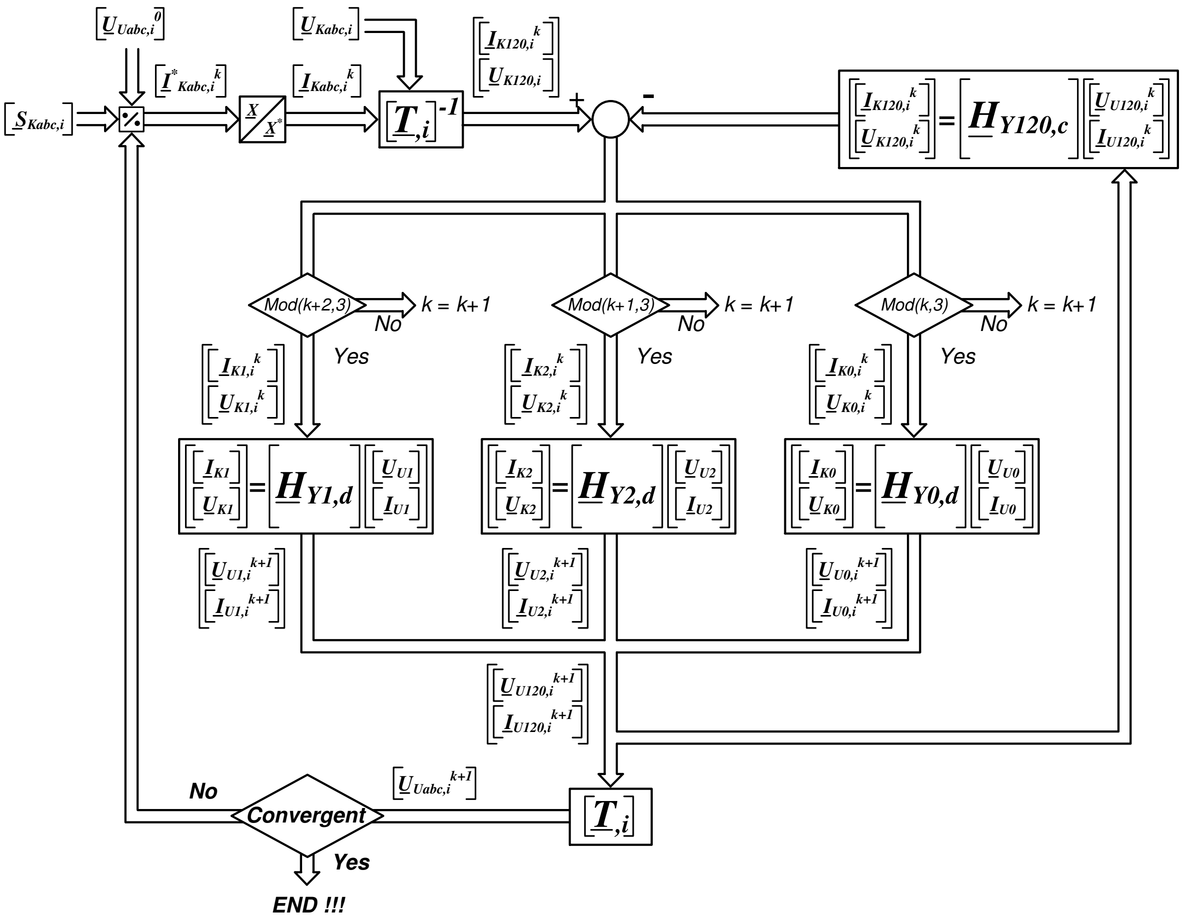


Fig. 6.14: Sequence hybrid load flow calculation flow chart

Where subscript *1, 2* and *0* stand for each sequence components, *abc* is for three-phase systems and *i* is a bus number. The superscript *k* stands for iteration step and *0* is an initial value. The transformation matrix from sequence components framework to three-phase system is defined by $[\underline{T}_{,i}]$.

It is noteworthy to mention that the calculation in the algorithm is divided into two main parts: the compensation part and the decoupling part. The algorithm is separated and calculated based on all sequences in the middle part of algorithm. The rest of algorithm is calculated based on complete system description. The target values or input values are defined by two types, known apparent power buses $[\underline{S}_{Kabc,i}]$ and known voltage buses $[\underline{U}_{Kabc,i}]$. Obviously, the load flow solutions are the voltage of unknown power buses $[\underline{U}_{Uabc,i}]$. To clarify the proposed algorithm in detail, the calculation process is explained in step as following:

- Firstly, the target apparent power $[\underline{S}_{Kabc,i}]$ is divided by the initial bus voltage vector $[\underline{U}_{Uabc,i}^{0}]$, in order to get the initial injection current vector $[\underline{I}_{Kabc,i}^{0}]$.
- Afterwards, the initial injection current vector is transformed to sequence components framework and combined with the known voltage buses vector $[\underline{U}_{K120,i}]$. This combination is forwarded to be an initial input of hybrid calculation.
- In the first loop of iteration, the compensation process is not started yet. The compensation process actives after finishing the first iteration loop, where the process is entered in the sequence hybrid calculation
- After the hybrid calculation, the results of all sequence components are combined and forwarded to the compensation block. At the same time, they are transformed into three phase system in order to update a new current injection vector
- Lastly, the calculation is stopped, when the load flow solution or unknown voltage vector $[\underline{U}_{Uabc,i}]$ is convergent.

According to the flow chart, it can be noticed that the MATLAB function *Mod* is existing in the flow chart. This function is implemented to indicate that the calculation of decoupling hybrid equation is arranged to execute in sequence. Based on the character of asymmetrical network, it is understandable that the network cannot be completely decoupled, even though the compensation process is provided. Therefore, the calculation of decoupling part is set to execute in sequence. The positive sequence is set to start in the first step because this sequence dominates the most character of power systems.

In summary, the proposed algorithm of sequence hybrid load flow calculation provides the simplest way to solve clustering power systems concept as well as the general asymmetrical load flow calculation. By the asymmetrical element compensation process, the system matrix can be decoupled; it results in fast computation time. In order to verify and figure out the application of cluster system analysis, the examined cluster systems are given later in the case study section.

It is worth to state that the proposed sequence hybrid analysis is able to solve all major interest of asymmetrical three-phase system analysis. However, few issues in power systems study, e.g. power quality and safety investigation, cannot be analyzed by this method, since the neutral cable is integrated into three-phase system matrix. Thus, the analysis of three-phase four-wire system is also concerned in this thesis. Clearly, the proposed algorithm for three-phase four-wire system is developed based on hybrid calculation in order to support the cluster system analysis.

6.5 Asymmetrical Hybrid Load Flow Calculation Method for Three-Phase Four-Wire Cluster System

According to the network structure, especially low voltage network, a role of neutral wire becomes obvious, e.g. protection standard issues on IEC 60364-1. Moreover, it is one of the indicators to observe power quality of either balanced or unbalanced condition. In general, the neutral wire effect is combined into phase wires by Kron's reduction method. It results in the unknown neutral wire currents and voltages.

In order to calculate those values, the efficient way to analyze is to represent a complete three-phase four-wire system in 4×4 matrix dimension instead of 3×3. Therefore, the three-phase four-wire hybrid load flow calculation method is developed. Initially, it is worth having a look on three-phase four-wire network; a simple three-phase four-wire network is shown in Fig. 6.15.

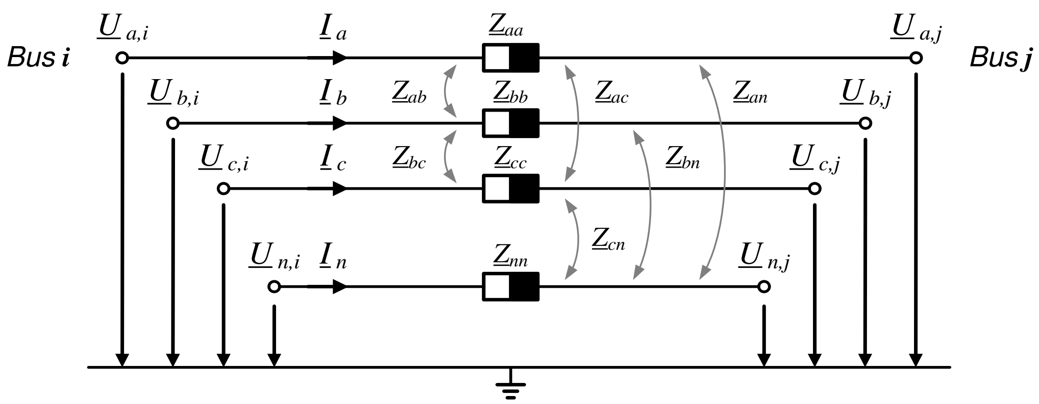


Fig. 6.15: Example of three-phase four-wire network

Since the analysis of neutral cable requires a complete network description, the three-phase four-wire cable in Fig. 6.15 must be modeled as in Eq. (6.28). Clearly, the impedance matrix model is described by 4×4 matrix dimension.

$$\underline{Z}_{abcn,ij} = \begin{bmatrix} \underline{Z}_{aa} & \underline{Z}_{ab} & \underline{Z}_{ac} & \underline{Z}_{an} \\ \underline{Z}_{ab} & \underline{Z}_{bb} & \underline{Z}_{bc} & \underline{Z}_{bn} \\ \underline{Z}_{ac} & \underline{Z}_{bc} & \underline{Z}_{cc} & \underline{Z}_{cn} \\ \underline{Z}_{an} & \underline{Z}_{bn} & \underline{Z}_{cn} & \underline{Z}_{nn} \end{bmatrix} \tag{6.28}$$

As a direct result, the network description between bus i and bus j can be obtained through Eq. (6.29). In this example, the bus admittance matrix dimension becomes 8×8.

$$\begin{bmatrix} \underline{I}_{abcn,i} \\ \underline{I}_{abcn,i} \end{bmatrix} = \begin{bmatrix} \underline{Y}_{abcn,ij} & -\underline{Y}_{abcn,ij} \\ -\underline{Y}_{abcn,ij} & \underline{Y}_{abcn,ij} \end{bmatrix} \begin{bmatrix} \underline{U}_{abcn,i} \\ \underline{U}_{abcn,j} \end{bmatrix} \tag{6.29}$$

After receiving the bus admittance matrix, the preparation process for hybrid matrix calculation in section 5.3.1 can be executed. It must be noted that the known voltage bus and the known current bus can be freely selected related to the analysis condition.

Performing full range system analysis, the complete system description may unfortunately take longer computational analysis time than sequence technique because of an increasing of matrix dimension, four times bigger. Nevertheless, the compensation process is unnecessary, contrary to sequence components technique, as the system is completely described by one matrix. According to this definition, it can be understood that the impedance hybrid matrix and the admittance hybrid matrix can be utilized in algorithm, since both are an inversion of each other. In the following section, the algorithm for three-phase four-wire hybrid calculation is pointed out and explained in detail.

6.5.1 Three-Phase Four-Wire Hybrid Load Flow Algorithm

Since the analysis of three-phase four-wire system requires complete network description, thus, it does not need to concern on any asymmetrical network condition. The load flow result is automatically targeted to whatever balanced or unbalanced study case because of the complete network description. To guarantee the cluster system analysis, the hybrid calculation is understandably selected as the key development platform. As the full matrix description is utilized in this case, the impedance hybrid matrix and the admittance hybrid matrix can be applied in algorithm because both hybrid matrixes are an inversion of each. Subsequently, the general hybrid equation for three-phase four-wire network are given as

$$\begin{bmatrix} [\underline{U}_{Uabcn}] \\ [\underline{I}_{Uabcn}] \end{bmatrix} = [\underline{H}_{Zabcn}] \cdot \begin{bmatrix} [\underline{I}_{Kabcn}] \\ [\underline{U}_{Kabcn}] \end{bmatrix} \tag{6.30}$$

The impedance hybrid matrix $[\underline{H}_z]$ is used in this algorithm, where the known current vector $[\underline{I}_{K,abcn}]$ and the known voltage vector $[\underline{U}_{K,abcn}]$ are the input vectors of load flow calculation. As all network elements are packed in one matrix, its load flow calculation algorithm can be presented in a simple flow chart as illustrated in Fig. 6.16.

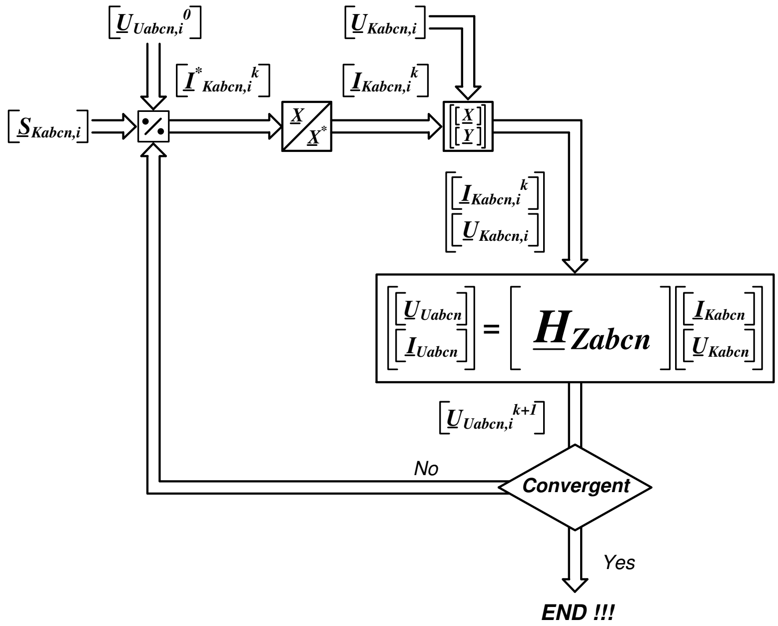


Fig. 6.16: Three-phase four-wire hybrid load flow calculation flow chart

Where subscript *abcn* stands for three phase systems including neutral, and *i* is a bus number. The superscript *k* stands for iteration step and *0* represents an initial value. Noticeably, the load flow algorithm for three-phase four-wire is executed through one hybrid equation.

Concerning the algorithm, the target values are defined by two types, i.e. known apparent power buses $[\underline{S}_{Kabcn,i}]$ and known voltage buses $[\underline{U}_{Kabc,i}]$. The solutions of load flow study are clearly the voltage of unknown power buses $[\underline{U}_{Uabc,i}]$. In the following, the calculation algorithm process is elucidated in step as:

- Firstly, the apparent power set point $[\underline{S}_{Kabc,i}]$ is divided by initial bus voltage vector $[\underline{U}_{Uabc,i}^{0}]$, in order to obtain the initial injection current vector $[\underline{I}_{Kabc,i}^{0}]$ for the first iteration.
- Next, the injection current vector $[\underline{I}_{Kabc,i}]$ is combined with the known voltage buses vector $[\underline{U}_{Kabcn,i}]$. This combination is forwarded to hybrid calculation process as input vector.

- After the hybrid calculation, the results of unknown bus voltage [$\underline{U}_{Uabcn,i}$] is fed back in order to update a new current injection vector for next iteration loop. When the unknown voltage vector is convergent, the calculation process is accomplished.

In conclusion, the proposed algorithm of three-phase four-wire system hybrid load flow calculation can solve the load flow problem of cluster power system under the asymmetrical condition as well as the symmetrical condition. Moreover, it also executes the study of neutral current and voltage, which can be referred to the study of power quality and safety issues. By describing all data of the network topology in one matrix, it directly results in a huge matrix dimension. Hence, it may consume more computational time than the sequence hybrid method. In addition, it is noteworthy to mention that both cluster analysis algorithms, i.e. sequence hybrid load flow and three-phase four-wire system hybrid load flow, are not only for the cluster system analysis but also for the general power systems analysis.

6.6 Summary

The hybrid approach is proposed as a main calculation technique for cluster systems analysis method. As a consequence, it is able to represent the behavior of interconnected clusters into the single cluster analysis, which results the system analysis in decoupling way. Due to asymmetrical conditions, which cannot be further ignored in distribution power systems management, the development of asymmetrical power flow analysis based on hybrid calculation is discussed and introduced in this chapter.

The conventional asymmetrical analysis methods including asymmetrical network description are primarily examined. As the first result, the combination between sequence components technique and hybrid method is developed and utilized for analyzing the asymmetrical cluster system. The algorithm flow chart in Fig. 6.14 shows that the sequence components technique provides the benefit in three-phase power systems analysis, e.g. simplifying network model and decreasing the analysis computational time. However, in several applications such as power quality and safety analysis, the neutral wire current and voltage are required to investigate. Usually, the neutral wire in any power flow study is merged into the phase system. Under this assumption, the power network has multi-grounded system, and the neutral wire is also grounded. As a result, the neutral voltage is equal to zero. Due to this reason, a complete power flow algorithm for three-phase four-wire system based hybrid calculation method is also evolved as an another option for asymmetrical cluster system analysis.

To accomplish the analysis of three-phase four-wire system, the complete power network description is needed. Regarding the complete power network description, the power flow algorithm is subsequently resulted in an easier way. Only one hybrid matrix is required for load flow analysis algorithm as noticed in algorithm flow chart in Fig. 6.15. Unfortunately, analyzing full power network description can consume more calculating time than sequence hybrid algorithm, because the matrix dimension is four times bigger than the one from sequence components technique.

Comparing between two proposed asymmetrical cluster system analysis algorithms, it must be noted that the major difference is its application. For example, the sequence hybrid calculation method is suitable for the cluster system analysis in medium voltage level and in high voltage level, since the power network is described by three-phase system. Oppositely, the analysis of the cluster in low voltage level requires the three-phase four-wire hybrid calculation method in order to investigate neutral current and voltage. Nonetheless, the sequence hybrid calculation method can be applied to the cluster in low voltage level as well, when the analysis of neutral voltage and neutral current is of no interest. Hence, the usage of both proposed hybrid calculation load flow algorithms can be freely selected based on the network topology and the study purpose.

Finally, the decoupling cluster system analysis can be performed in the entire cluster power systems from the bottom local cluster area, which the majority is dominant by the asymmetrical condition, to the top cluster area in symmetrical transmission system. In addition, both analysis algorithms, i.e. sequence hybrid load flow and three-phase four-wire system hybrid load flow, are not only for the cluster system analysis but also for the general power systems analysis. In order to validate the proposed algorithm and figure out its application for cluster system analysis, the case studies are provided in the next chapter.

7. Validation of Asymmetrical Hybrid Load Flow Algorithm

The cluster system analysis is fundamental function in cluster system management and optimization. To accomplish cluster analysis strategy, as mentioned in Chapter5, the hybrid calculation approach is subsequently proposed to deal with the interconnected clusters network structure. Because hybrid approach offers a possibility to represent the behavior of connected clusters, which results the cluster analysis in decoupling way. Consequently, the contribution in the final state is focused on the development of the asymmetrical cluster analysis method based on the hybrid calculation technique. The analysis under asymmetrical conditions is required, since the future power systems could not anymore concern as symmetrical system due to penetration of electric vehicle, single-phase feed in of home PV systems, etc. As results, the sequence hybrid analysis method and the three-phase four-wire hybrid analysis method are evolved through a different application as discussed in Chapter6.

To validate the proposed sequence hybrid load flow method and three-phase four-wire hybrid load flow method, three analysis case studies are set as below:

- Case1: Low voltage network
- Case2: IEEE 123 nodes test feeder
- Case3: Interconnected clusters system

Three different test scenarios are examined in order to illustrate different applications of analysis method. The simulation results are evaluated and verified through the power systems analysis software, DIgSilent PowerFactory. Furthermore, the results from the classical three-phase Newton-Raphson method [142] are used as the reference as well. Brief explanations of three case studies are given as following:

The first case study is aimed to verify both proposed analysis methods with the commercial simulation program, DIgSilent. In this case, the real distribution network from DISPOWER project is selected to investigate. This examined network is existed in Italy urban low voltage network. The cables are underground three phases with neutral cable. The applied power is considered as asymmetrical spot load and asymmetrical generation.

In the second case, the IEEE 123 nodes test feeder is utilized. This test feeder provides the complete asymmetrical network, where the network topology is described by the multi-phase systems. The applied power is considered as unbalanced spot loading. Due to the limitation of DIgSilent program, it is not able to define asymmetrical power cable in its element library. Therefore, the three-phase Newton-Raphson method is only used for the load flow results comparisons. Since, this case study has the maximum node number among all examined network. The discussions based on the algorithm performance, advantages and disadvantages are given.

As the hybrid calculation technique is proposed as the solution for the analysis of clustering power systems, the application of both developed hybrid analysis algorithms is focused and worthy to discuss in the third case study. The IEEE 37 nodes test feeder is considered as a based network topology. In order to present the character of interconnected cluster systems, some part of examined test feeder is modified. As a result, the hybrid technique is verified and able to fulfill the requirement of cluster analysis strategy.

All examined case studies or rather the proposed algorithms are performed on MATLAB R2012a. The network component models, i.e. distribution transformer, and the examined network parameter of each case study, are detailed in Chapter 9.

7.1 Case Study 1: Low Voltage Network

One development target of sequence hybrid and three-phase four-wire hybrid calculation is to solve load flow problem under the asymmetrical conditions, which can be found in distribution network system. Therefore, the existed low voltage network is considered in this study as one of verification tests. The examined network is selected from the report "Classification of Low Voltage Grid based on Energy Flows and Grid Structure", DISPOWER project [151], where the Italian urban low voltage network is chosen and minor modified, as presented in Fig. 7.1. The studied network is described that 10 kV medium voltage level as a slack bus. It is connected to the low voltage level through 2MW 10/0.4 kV Dyn5 distribution transformer. On the low voltage network, it is consisted of four feeders, which are an underground three phases with a neutral cable. The applied power is considered as an asymmetrical spot load and generation. All simulated parameters, transformer, cable, and applied load data are listed in section 9.2.1. The objective of this case study is to validate and evaluate the numerical accuracy the proposed algorithms. Therefore, the DIgSilent PowerFactory program is selected to be a reference. Furthermore, the classical three-phase system analysis using Newton-Raphson method [142] is also concerned as another reference. However, it must be noted that both proposed algorithms are developed based on different aspect regarding the investigation of the neutral cable. Thus, the study and comparative results are divided into two examined parts, without and with neutral cable, respectively. Due to the limitation of PowerFactory program element library, which is not able to parameter an asymmetrical condition of cable, only unbalance spot load and generation are concerned as the asymmetrical conditions in this study.

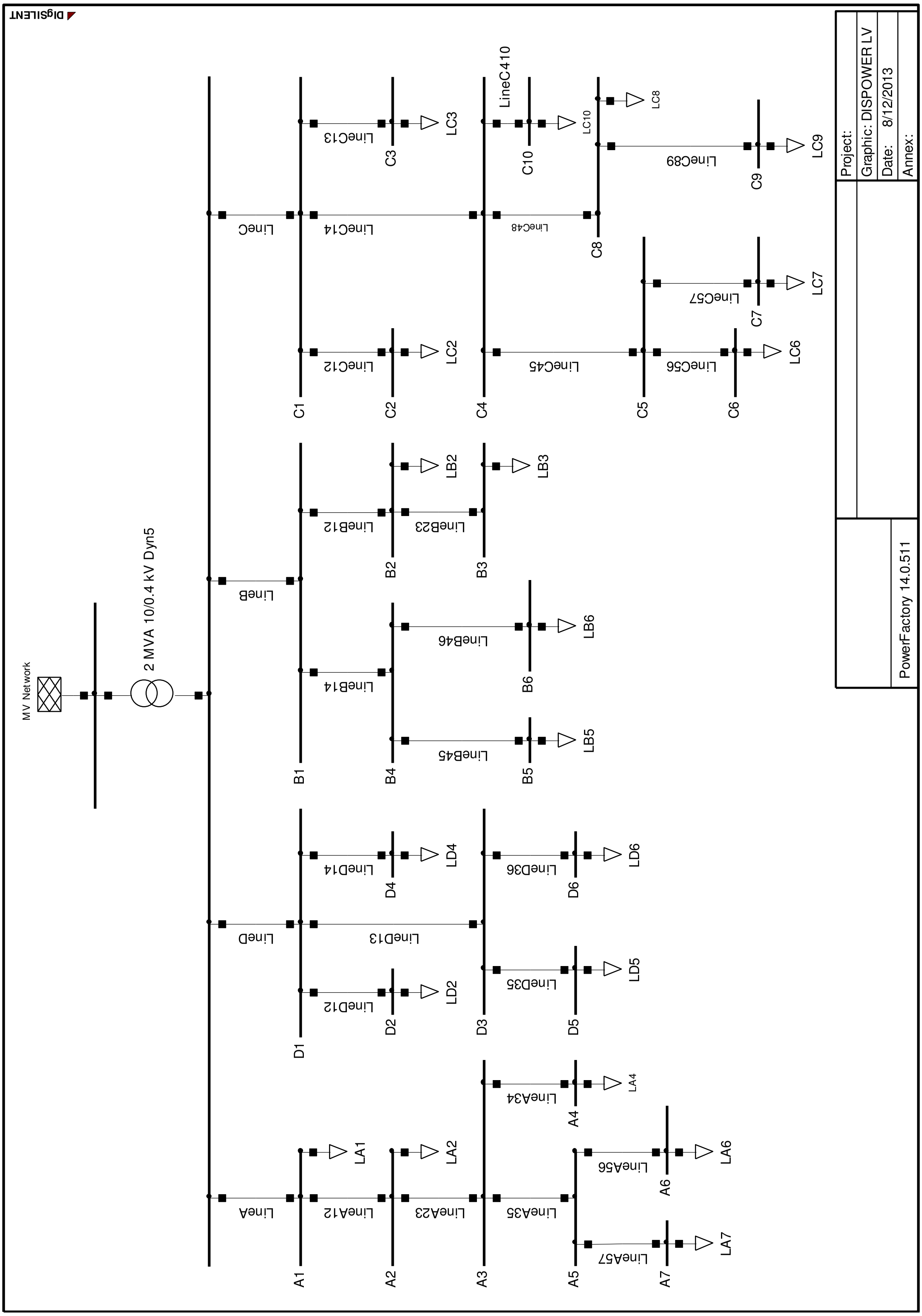


Fig. 7.1: Examined low voltage network [151]

According to the proposed sequence hybrid algorithm, a line to neutral voltage is firstly examined. It means that the effect of neutral cable is combined into phase system. Hence, the classical analysis, three-phase system Newton-Raphson, is also used as reference. Comparative results of phase *a* to neutral voltage between three analysis platforms are illustrated in Table 7.1; a few nodes of each feeder are selected to present. The calculation results of the proposed sequence hybrid algorithm are slightly different from the results from DIgSilent program. The difference in an absolute voltage can be observed in the fifth decimal digit, which is 2 mV, and the voltage angle at the third digit. The difference can cause by network element model; however, this difference is acceptable.

On the other hand, the proposed sequence hybrid algorithm results the same value as three-phase system Newton-Raphson analysis, because both algorithms are used the same buses admittance matrix, which guarantees same network element description. Lastly, the comparative results with DIgSilent and three-phase Newton-Raphson prove that the proposed sequence hybrid analysis is reliable in the result accuracy.

Table 7.1: Comparative load flow results of selected nodes

	DIgSilent		3-Phase N-R		Sequence Hybrid	
Node	$\|U_{an}\|$	angle U_{an}	$\|U_{an}\|$	angle U_{an}	$\|U_{an}\|$	angle U_{an}
	[pu.]	[deg.]	[pu.]	[deg.]	[pu.]	[deg.]
Main LV	0.99754	-150.56528	0.99753	-150.56447	0.99753	-150.56447
A3	0.97512	-150.89688	0.97511	-150.89584	0.97511	-150.89584
A7	0.96707	-150.91375	0.96706	-150.91290	0.96706	-150.91290
B2	0.98484	-150.49296	0.98483	-150.49217	0.98483	-150.49217
B4	0.97871	-150.42325	0.97870	-150.42246	0.97870	-150.42246
C4	0.95680	-151.16620	0.95679	-151.16532	0.95679	-151.16532
C9	0.95400	-151.34388	0.95399	-151.34297	0.95399	-151.34297
D2	0.98813	-150.66315	0.98812	-150.66234	0.98812	-150.66234
D5	0.99461	-150.54961	0.99460	-150.54881	0.99460	-150.54881

The results in Table 7.1 are concerned only phase to neutral voltage. Hence, the effect of neutral cable is taken into account in the second part of this study. This means that the mathematic model or rather bus admittance matrix of cable element has to be described with 4×4 matrix dimension. Consequently, the three-phase four-wire hybrid load flow algorithm is investigated. As a direct result, the neutral to earth voltage can be found in this execution.

To emphasize the accuracy of proposed sequence hybrid algorithm, an absolute voltage difference of each node is depicted in Fig. 7.2. The absolute difference is calculated by using the different results between DIgSilent and sequence hybrid algorithm of phase *a* to neutral voltage. Since, the difference is in the range of 0.01 ‰. It means that the developed algorithm is reliable.

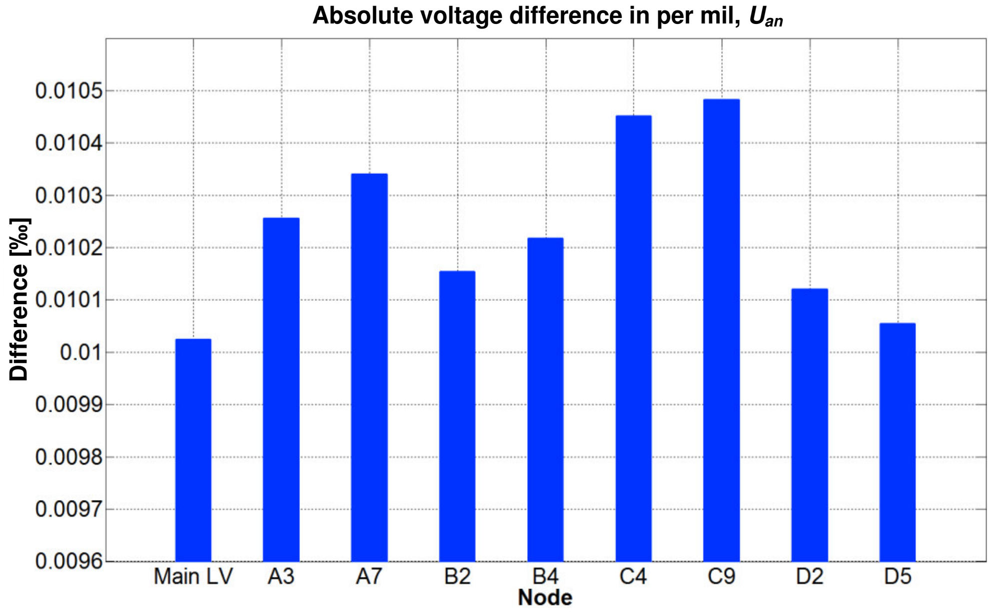


Fig. 7.2: U_{an} voltage difference between DIgSilent and sequence hybrid algorithm

To verify the three-phase four-wire hybrid algorithm, the results of DIgSilent program is used as the reference. The comparative results of phase *a* voltage and neutral voltage are shown in Table 7.2. Due to the algorithm of Newton-Rapson analysis, which is developed for three-phase system, it is excluded in this comparison.

Table 7.2: Comparative load flow results of selected nodes

Node	DIgSilent				3-Phase 4-Wire Hybrid			
	$\lvert U_a \rvert$ [pu.]	angle U_a [deg.]	$\lvert U_n \rvert$ [pu.]	angle U_n [deg.]	$\lvert U_a \rvert$ [pu.]	angle U_a [deg.]	$\lvert U_n \rvert$ [pu.]	angle U_n [deg.]
Main LV	0.99754	-150.56528	0	0	0.99759	-150.56521	0	0
A3	0.97464	-150.74878	0.00256	-50.02517	0.97469	-150.74869	0.00256	-50.02518
A7	0.96727	-150.76245	0.00256	-65.39705	0.96732	-150.76236	0.00256	-65.39711
B2	0.98399	-150.54411	0.00122	75.50988	0.98404	-150.54405	0.00122	75.50968
B4	0.97753	-150.51635	0.00198	82.97989	0.97758	-150.51629	0.00197	82.97975
C4	0.95872	-150.88680	0.00505	-83.36855	0.95877	-150.88669	0.00504	-83.36864
C9	0.95559	-150.97748	0.00631	-75.73119	0.95564	-150.97737	0.00631	-75.73126
D2	0.98851	-150.62173	0.00081	-89.08449	0.98856	-150.62166	0.00081	-89.08451
D5	0.99452	-150.55993	0.00020	91.85520	0.99456	-150.55986	0.00020	91.85507

After examining the comparative results, it found that there is a small difference between both analysis methods. The difference can be noticed on phase voltage in the fifth decimal digit. Concerning the neutral voltage, a tiny difference can also be seen. In order to further investigate the results of this algorithm, the phase to neutral voltage is calculated. The node C9 is subsequently selected to consider. After calculation, the magnitude of phase *a* to neutral voltage is equal to 0.95405 pu., and the voltage angle is -151.34383 degree. Comparing this outcome with the previous result in Table 7.1, the result shows the difference in the fifth decimal digit as well. Hence, it proves that the proposed three-phase four-wire algorithm is properly worked with this small different range. Similarly to the previous discussion over algorithm accuracy, the absolute voltage difference of phase *a* voltage is examined. Calculating the voltage different results between DIgSilent and the three-phase four-wire hybrid algorithm, the results are consequently illustrated in Fig. 7.3. It can be seen that the maximum difference is around 0.055 ‰ (10mV). Therefore, it guarantees that the three-phase four-wire hybrid algorithm is trustworthy.

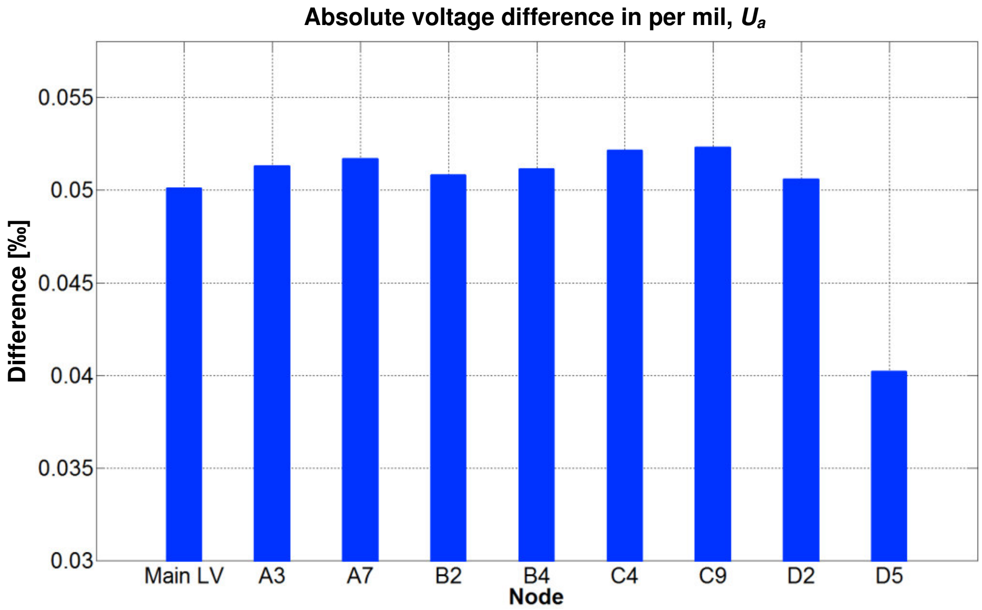


Fig. 7.3: U_a difference between DIgSilent and three-phase four-wire hybrid algorithm

In conclusion, this case study provides the validation of both proposed asymmetrical load flow methods with the comparison with DIgSilent PowerFactory and three-phase Newton-Raphson method. After inspecting, all three methods result the same results. It guarantees that the proposed sequence hybrid load flow algorithm and three-phase four-wire hybrid load flow algorithm can work properly.

7.2 Case Study 2: IEEE 123 nodes Test Feeder

According to symmetrical cable on the previous case study, it means that the compensation function of proposed sequence hybrid algorithm is not yet executed or tested. Consequently, in this test scenario, the IEEE 123 node test feeder is taken into account because the test feeder offers full asymmetrical condition. The network topology is structured by the multi-phase systems as well as untransposed power cables. Furthermore, the loads are described with strong unbalanced spot loading. The test feeder operates at a nominal voltage of 4.16 kV.

While this is not a popular voltage level, it provides voltage drop problems. To handle this problem, the application of voltage regulators and shunt capacitors is needed. Unfortunately, the model of voltage regulator is not provided in this thesis. Therefore, this test feeder has been modified based on a publication in [152]. This publication introduces the reactive power injection profile to handle with voltage drop problem.

The modified test feeder is illustrated in Fig. 7.4. White dots are the modified nodes, where the reactive injection power is applied. Another modification is the substation model; it is replaced by 115/4.16kV 5MVA Dyn5 distribution transformer. The cable and load configurations are kept at the provided data from IEEE [153]. In an examination, all switch configurations are set to close. All network parameters of this test scenario and the reactive injection power profile are detailed in section 9.2.2.

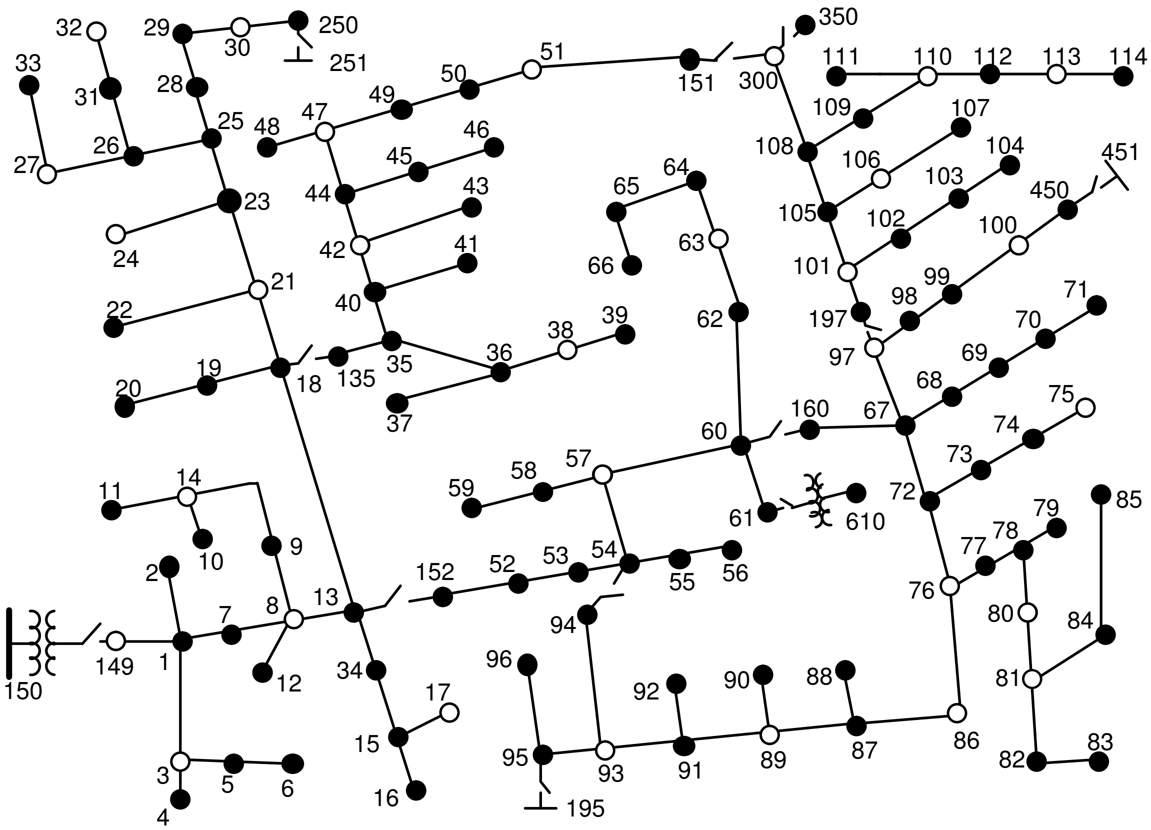


Fig. 7.4: Modified IEEE 123 nodes test feeder [152]

Regarding the investigation program, the DIgSilent program is, unfortunately, not included in this study, since it is not able to describe asymmetrical power cable of IEEE test feeder. Hence, the three-phase Newton-Raphson method, the proposed sequence hybrid method and the three-phase four-wire hybrid method are considered in this test scenario. It is noteworthy to mention that the cable configuration of IEEE test feeder is defined with 3×3 matrix dimension, and the neutral cable is integrated into phase cable. Even though the exanimated grid is able to be investigated through three-phase four-wire hybrid algorithm, the load flow results come up with phase to neutral voltage. Obviously, the neutral voltage remains as an unknown value. To validate the proposed algorithm, the comparative results of phase *a* to neutral voltage from three mentioned methods are shown in Table 7.3. The load flow results of all methods are identical. This can occur when all analysis methods are utilized the same buses admittance matrix.

Table 7.3: Comparative load flow results of selected nodes

	3-Phase N-R		Sequence Hybrid		3-Phase 4-Wire Hybrid	
Node	$\lvert U_{an} \rvert$ [pu.]	angle U_{an} [deg.]	$\lvert U_{an} \rvert$ [pu.]	angle U_{an} [deg.]	$\lvert U_{an} \rvert$ [pu.]	angle U_{an} [deg.]
8	0.9651	-152.5313	0.9651	-152.5313	0.9651	-152.5313
18	0.9431	-153.4041	0.9431	-153.4041	0.9431	-153.4041
30	0.9398	-153.6263	0.9398	-153.6263	0.9398	-153.6263
44	0.9367	-153.6395	0.9367	-153.6395	0.9367	-153.6395
46	0.9352	-153.6432	0.9352	-153.6432	0.9352	-153.6432
54	0.9430	-153.6911	0.9430	-153.6911	0.9430	-153.6911
60	0.9280	-154.8820	0.9280	-154.8820	0.9280	-154.8820
66	0.9272	-155.0054	0.9272	-155.0054	0.9272	-155.0054
72	0.9225	-155.2746	0.9225	-155.2746	0.9225	-155.2746
81	0.9200	-155.5097	0.9200	-155.5097	0.9200	-155.5097
87	0.9192	-155.2441	0.9192	-155.2441	0.9192	-155.2441
108	0.9173	-155.4196	0.9173	-155.4196	0.9173	-155.4196
114	0.9032	-155.6701	0.9032	-155.6701	0.9032	-155.6701
450	0.9234	-155.2429	0.9234	-155.2429	0.9234	-155.2429

To solve the untransposed power cable and the multi-phase network based on sequence technique, it requires the compensation technique to extract the asymmetrical elements in buses hybrid matrix in order to decouple matrix in three frameworks and execute sequence analysis. The comparative results can be concluded that the proposed compensation technique for sequence hybrid algorithm is functional and able to solve any asymmetrical condition. Furthermore, this case study proves the three-phase four-wire hybrid analysis algorithm in the part of multi-phase network analysis. Those mentioned issues prove and ensure both proposed algorithms in reliability and accuracy.

Since this test feeder provides the strong unbalanced condition, it is worthy to observe the voltage profile and stability. The three phase load flow results of some selected nodes are portrayed in Table 7.4. It can be noticed that the examined system has strong unbalanced condition e.g. the amplitude differences between phases of node18. This is an effect of strong unbalanced load as well as multi-phase network. As found on node 44, node 96, and node114, the connection through these nodes are structured by the single phase system.

Table 7.4: Selected nodes three-phase load flow results

Node	$\|U_{an}\|$ [pu.]	angle U_{an} [deg.]	$\|U_{bn}\|$ [pu.]	angle U_{bn} [deg.]	$\|U_{cn}\|$ [pu.]	angle U_{cn} [deg.]
8	0.9651	-152.5313	0.9984	88.2363	0.9857	-30.9626
18	0.9431	-153.4041	0.9943	87.4375	0.9774	-31.0800
30	0.9398	-153.6263	0.9962	87.4165	0.9750	-31.1175
44	0.9367	-153.6395	0.9895	87.1739	0.9748	-31.2353
46	0.9352	-153.6432	0.000	0.0000	0.0000	0.0000
54	0.9430	-153.6911	0.9939	87.4253	0.9721	-31.2673
60	0.9280	-154.8820	0.9876	86.8264	0.9590	-31.6875
66	0.9272	-155.0054	0.9842	87.0297	0.9468	-31.7020
72	0.9225	-155.2746	0.9852	86.5199	0.9551	-31.8305
81	0.9200	-155.5097	0.9848	86.3898	0.9516	-31.9099
87	0.9192	-155.2441	0.9785	86.1607	0.9575	-31.9869
96	0.0000	0.000	0.9762	86.0874	0.0000	0.0000
108	0.9173	-155.4196	0.9875	86.3467	0.9571	-31.6019
114	0.9032	-155.6701	0.0000	0.0000	0.0000	0.0000
450	0.9234	-155.2429	0.9849	86.5666	0.9553	-31.8743

Regarding the huge amount of node in this case, it is subsequently a good example to observe the performance of proposed algorithm. In order to figure out algorithm performance, the iteration step and the computational time of case study1 and case study2, which are performed by the three-phase Newton-Raphson, the sequence hybrid and three-phase four-wire hybrid method, are taken into account. It is important to mention that all algorithms are run on MATLAB R2012a, Intel Core 2 Duo CPU 3.00 GHz RAM 4.00GB 32Bit-System. The load flow results are evaluated by mean square error. The algorithm is stopped, when the error is less than 1 µV. The comparison of iteration step and computational time of all cases are illustrated in Fig. 7.5.

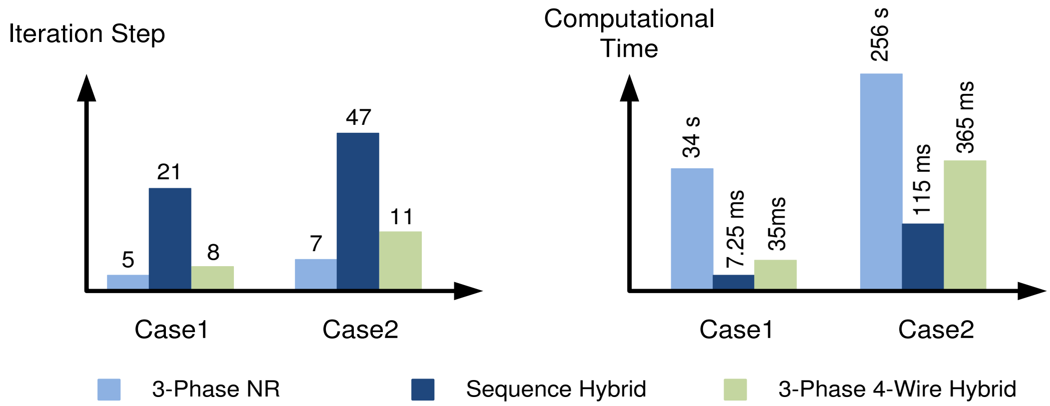


Fig. 7.5: Algorithm performance comparison

According to the performance comparison, an ascending order of iteration step can be arranged from Newton-Raphson, three-phase four-wire hybrid, and sequence hybrid. It can be expected that Newton-Raphson process requires less iteration steps than hybrid calculation, since the hybrid algorithm is basically based on the current iteration process, as indicated in Fig. 7.5. Comparing two proposed hybrid algorithms, the major difference is the dimension of hybrid matrix or rather buses admittance matrices. The sequence components technique splits complete network matrix into three matrixes; this process is not done in three-phase four-wire method. As a consequence, the three-phase four-wire algorithm needs less iteration steps than sequence hybrid approach. However, it can be noticed that the iteration steps and computational time are inversely proportional. Finally, it is worth to mention that the performance load flow algorithm is a matter of accuracy or fast calculation, which is related to the maximum allowance error of calculated variable, e.g., node voltage error and node injection power error.

In summarization, the proposed sequence hybrid load flow calculation and three-phase four-wire hybrid analysis are recently tested and verified. Both algorithms are able to deal with the unbalanced load, unbalanced feed in power and the multi-phase network systems. As mentioned that the analysis based on hybrid calculation technique is proposed for cluster system analysis. Therefore, the interconnected clusters network analysis based on hybrid application is given and discussed in the next case study.

7.3 Case Study 3: Interconnected Clusters System

When the clustering power systems concept is targeted to structure the future network system as interconnected grids and each cluster is aimed to be operated like TSO, the traditional analysis strategy must be adapted in order to support and deal with many interconnected clusters. The hybrid calculation technique is subsequently proposed, since the behavior of neighbor clusters can be integrated into the analysis, which leads to decoupling analysis based on cluster area itself. After the sequence hybrid and the three-phase four-wire hybrid load flow calculation are verified through previous case studies, their application to interconnected clusters analysis is focused in this case study.

To perform and assure the cluster analysis strategy, the IEEE 37 nodes test feeder is taken into account as a base network. In order to describe the character of interconnected clusters network, the 37 nodes feeder is modified. The modified network has three cluster levels: node 799 is defined as the superordinate cluster level, and node 725 and 775 are the subordinate cluster level, as depicted in Fig. 7.6. The other modification point is a substation model. It is replaced with 230/4.8kV 2.5MVA Dyn5 distribution transformer. All cable and load configurations are kept as provided data from IEEE [153].

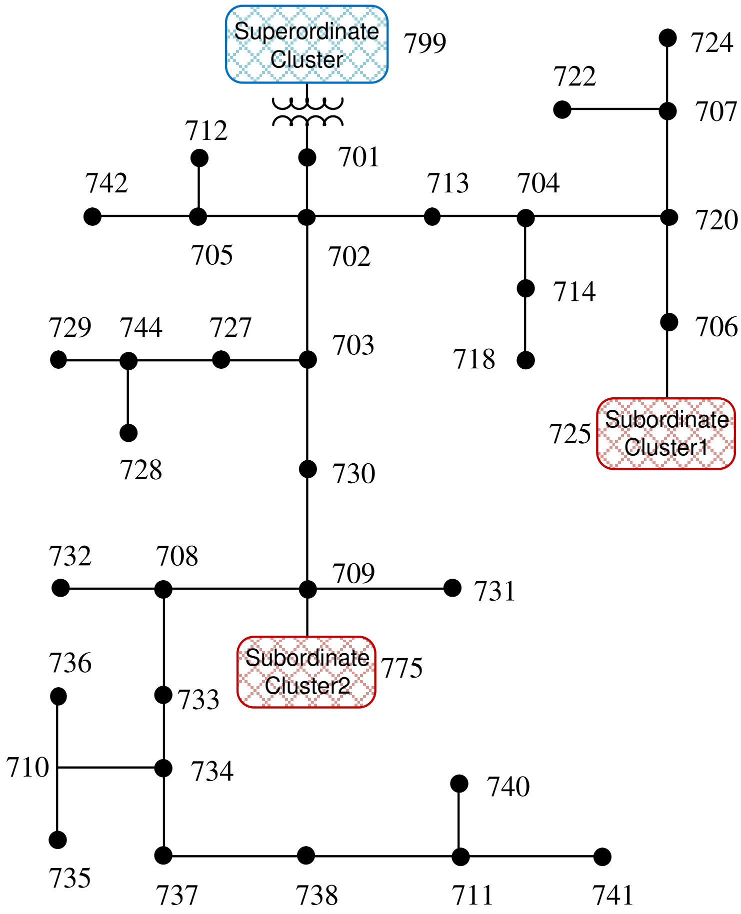


Fig. 7.6: Modified IEEE 37 nodes test feeder to interconnected clusters network

As emphasized, the cluster analysis is aimed to operate based on each cluster. Thus, it requires the interconnected clusters voltages to be included into the analysis in order to describe their behaviors. To assume or get a good interconnected cluster voltage, the test system is firstly examined by three-phase Newton-Raphson method in order to assume interconnected clusters condition. The superordinate cluster is defined as the slack bus. Both subordinate clusters are defined as the injection power bus, where $\underline{S}_b$ and $\underline{S}_{abc}$ are injected by the subordinate cluster1 and the subordinate cluster2 are 42+j21 kVA and 60+j15 kVA, respectively. After calculating, the interconnected clusters voltages are obtained. According to those results, the interconnected clusters voltages are used to apply for proposed cluster analysis method. The interconnected clusters voltages are stated in Table 7.5.

As regards IEEE 37 nodes test feeder, the cable configuration is described with underground cable, where the neutral cable is integrated into phase system. Subsequently, the sequence hybrid algorithm is a right choice for this study. However, the three-phase four-wire hybrid algorithm is still able to perform and observe in this case.

Table 7.5: Applied voltage of cluster node

Cluster	$\lvert U_a \rvert$	angle U_a	$\lvert U_b \rvert$	angle U_b	$\lvert U_c \rvert$	angle U_c
	[pu.]	[deg.]	[pu.]	[deg.]	[pu.]	[deg.]
Superordinate Cluster	1.000	0.000	1.000	-120.00	1.000	120.00
Subordinate Cluster1	0.962	-151.553	0.992	89.035	0.960	-31.546
Subordinate Cluster2	0.980	-151.248	0.985	89.239	0.969	-31.672

After investigating both proposed algorithms, the interesting issue is the injection power of superordinate cluster node and subordinate cluster nodes. Since the assumed interconnected clusters voltages are obtained from the results of Newton-Raphson analysis, thus, the calculation of slack injected power from proposed analysis must result in same value. Especially, the injection power of subordinate clusters has to produce the same value because these injection powers are given in Newton-Raphson analysis. The injection power of cluster nodes is shown in Table 7.6. Clearly, the results are identical. The same results of injection power are one of validation strategies of proposed analysis methods.

Table 7.6: Back calculated injection power of cluster node

Cluster	P_a	Q_a	P_b	Q_b	P_c	Q_c
	[kW]	[kvar]	[kW]	[kvar]	[kW]	[kvar]
Superordinate Cluster	856.02	583.97	601.82	385.92	900.44	264.81
Subordinate Cluster1	0.00	0.00	42.00	21.00	0.00	0.00
Subordinate Cluster2	20.00	5.00	20.00	5.00	20.00	5.00

To observe the voltage profile of examined interconnected clusters system and to ensure the proposed sequence hybrid and three-phase four-wire analysis method again, the comparative load flow results, phase *a* voltage, of selected nodes are shown in Table 7.7. It is obvious that the comparative results are identical, as all algorithm is utilized the same buses admittance matrix. Regarding the voltage profile, it can be observed that the profile of examined system is very unbalanced. This can be referred to the description in IEEE test feeder document, which the 37 nodes test feeder is defined with very unbalanced loading character.

In summary, this case study expresses the application of hybrid calculation method for the clustering power systems analysis. Since, the cluster analysis is aimed to operate based on each cluster area, so the voltage of interconnected clusters has to be included in order to describe the behavior of the interconnected clusters. After examining, the proposed sequence hybrid and three-phase four-wire hybrid method can fulfill the cluster strategy aspects. Furthermore, the comparative results provide the reliability of proposed method. It means that the proposed algorithms can function properly.

Table 7.7: Comparative load flow results of selected nodes

Node	3-Phase N-R		Sequence Hybrid		3-Phase 4-Wire Hybrid	
	$\lvert U_{an}\rvert$ [pu.]	angle U_{an} [deg.]	$\lvert U_{an}\rvert$ [pu.]	angle U_{an} [deg.]	$\lvert U_{an}\rvert$ [pu.]	angle U_{an} [deg.]
702	0.981	-151.2468	0.981	-151.2468	0.981	-151.2468
704	0.9792	-151.2441	0.9792	-151.2441	0.9792	-151.2441
720	0.9805	-151.2201	0.9805	-151.2201	0.9805	-151.2201
724	0.9822	-151.0651	0.9822	-151.0651	0.9822	-151.0651
729	0.9675	-151.3954	0.9675	-151.3954	0.9675	-151.3954
730	0.9644	-151.5248	0.9644	-151.5248	0.9644	-151.5248
732	0.9580	-151.6323	0.9580	-151.6323	0.9580	-151.6323
734	0.9484	-151.7781	0.9484	-151.7781	0.9484	-151.7781
738	0.9397	-151.8915	0.9397	-151.8915	0.9397	-151.8915
741	0.9401	-151.9446	0.9401	-151.9446	0.9401	-151.9446
742	0.9814	-151.2495	0.9814	-151.2495	0.9814	-151.2495

7.4 Summary

The hybrid calculation technique is proposed to be the key strategy for cluster system analysis. The operation of interconnected cluster network, which is aimed to process based on each area, becomes more obvious because hybrid technique can integrate the characteristics of connected clusters into the analysis. Besides the cluster analysis strategy, the unbalanced conditions are also taken into account e.g. distribution network topology. It is an important factor to indicate the success of active distribution control area. Therefore, the proposed algorithms, sequence hybrid and three-phase four-wire hybrid calculation, are not only evolved to deal with symmetrical cluster network, but also with the asymmetrical problem. It must be noted that both algorithms are developed in different aspects. The sequence hybrid method is basically developed to solve asymmetrical three-phase load flow problem, which the main interest is obviously the voltage of three-phase. Unfortunately, a problem of three-phase distribution system with neutral cable is unsolvable, e.g. NEV, since the neutral cable in the most power flow study is not explicitly represented and commonly merged into phase wires. Then, the neutral current and voltage stay as unknown values. Consequently, the three-phase four-wire hybrid calculation is pointed out for this issue. The interest of neutral values is important in some analysis applications like power quality, safety, loss, etc.

To validate the proposed methods, the comparative results are obtained from several case studies by using existing low voltage network and IEEE test feeders with asymmetrical load and generation. As a result, both methods provide the same load flow results as DIgSilent PowerFactory and three-phase Newton-Raphson method. Nevertheless, small difference, 0.05‰ (10 mV), can be found by the comparison with DIgSilent PowerFactory program. This can be caused by the difference of network model or buses admittance matrix. On the other hand, the three-phase Newton-Raphson method, which utilized the same buses admittance matrix, delivers the identical results as proposed algorithms. Concerning the comparison of two proposed hybrid algorithms, the main difference except the load flow study issue is the dimension of buses admittance matrix, which sequence components technique has less dimension than three-phase four-wire method. As a consequence, the sequence hybrid method consumes less computational time than three-phase four-wire hybrid calculation, although more iteration steps are required. However, it must be stated that both algorithms are reliable and can work appropriately.

Furthermore, the test scenario of interconnected clusters is also given. Three interconnected cluster levels, i.e. superordinate, ordinate, and subordinate, are examined, where the ordinate level is considered as the interested cluster area. This means that the imported voltage from superordinate and subordinate cluster is required in order to describe their character into the ordinate cluster. The assumed situation of interconnected clusters network is firstly designed and produced by the three-phase Newton-Raphson analysis method. Afterwards, the hybrid algorithms are come out and performed in order to represent that interconnected clusters system situation of both algorithms are able to recreate the assumed situation with the same result. This proves that the hybrid calculation method can realize the aim of clustering power systems philosophy. Since both hybrid analysis methods are intended to include the behavior of interconnected cluster into the analysis, therefore, the cluster analysis results in decoupling systems analysis. In addition, the proposed hybrid analysis method is not only used for the cluster analysis purpose, but it is also able to be utilized in the general power systems analysis.

In conclusion, the cluster power flow analysis based on hybrid calculation method provides the simplest way to solve the planning and organization problem of cluster systems. The cluster power flow analysis is finally a key function of DMS. Finding the optimum value for cluster control applications, i.e. PC and SC, as well as optimization and management process of cluster systems can be accomplished. Lastly, the chance to achieve the automated cluster management and optimization in order to empower the distribution network becomes apparent. The operation gap between transmission and distribution system can be closed with the compatibility.

8. Conclusions and Future Works

As the challenge of integrating a large numbers of DG based DERs in the power systems and empowering the distribution network has been taken into account to achieve smart energy supply systems, the clustering power systems philosophy is subsequently evolved to be one of the future power supply systems solution. This clustering philosophy is developed and announced through the department of Power Systems and Power Economics, at South Westphalia University of Applied Sciences, Soest, Germany. Besides this development, many strategies have been successfully introduced, e.g. recycling of hierarchical conventional control strategy for distribution power generation. These strategies confirm that the clustering philosophy is targeted to establish the downsized conventional control process in distribution network, which leads to the compatibility in grid operation between transmission system and distribution system.

To carry out the advantages and further develop on the clustering philosophy, this research study has proposed the analysis strategy for clustering power systems network. This analysis strategy is a solution to accomplish the cluster network operation, since it is the fundamental function for system planning and optimization. In order to draw out the importance of cluster analysis strategy, the major accomplishments of this research study are summarized in this section as well as the recommended future work.

8.1 Conclusion

As emphasized that the key to complete cluster network management and operation is the cluster analysis, or in another word the cluster load flow analysis. In order to achieve this target strategy, the stepwise study process is required. Hence, the precise development steps are concluded in the following.

Initially, the main essential study issue is the clustering power systems philosophy. This concept structures the electricity grid especially distribution network in a new aspect, which provides a simple way to organize and has moreover the compatibility with conventional grids. Thus, the cluster network structure is firstly investigated. Since the clustering concept keeps the advantages of conventional interconnected transmission systems, it results directly in interconnected clusters network, and in multi-level of interconnected networks. Thus, the term of superordinate, ordinate, and subordinated are evolved and utilized for describing multi-level structure. This interconnected clusters structure can be implied as the downsized of ENTSO-E. According to this fact, the cluster philosophy is not only focused on technical grid service issue but also market issue.

To serve and operate interconnected clusters network, the recycling of hierarchical conventional control strategy for distribution power generation is secondly investigated. This strategy is supported by the establishing cluster controller or distribution management systems. Since it is basically developed based on conventional control strategy, it delivers a great benefit in the compatibility with conventional power systems process. This is one of the solution massages for future power systems that any novel development must be coexisted and must not ruin the existing conventional system. The application of SC is consequently pointed out and considered as a fundamental function of interconnected clusters network, because it offers a functionality of power balancing within cluster area and power transferring between interconnected clusters. Regarding this fact, the approach of multi-level SC is come out and successfully examined based on mathematical description at the beginning. To take the advantage and forward this concept, this research study is shown and elucidated by the term of horizontal control application and vertical control application. Both applications are introduced not only for the SC, but also for further control function e.g. TC. The horizontal- and vertical control application clarifies the operation of interconnected clusters network. The horizontal application can be considered as the traditional control function of TSO or the power transfer in the same cluster level. The vertical control application is concerned as the operation of different cluster level. This application can be implied for the reversion of power flow process from low voltage level to high voltage level, which is expected in the future electricity network. Combining these two modes of application, it leads the entire supply systems to be the active control network. Therefore, each cluster area can be controlled and managed based on area itself including the interaction with connected clusters, as illustrated in the verification test scenarios.

Up to this point, it has to be noted that the cluster operation is basically described through conventional control strategy, PC and SC. To move towards cluster operation, the role of management or supervisory control is taken into account. Hence, the cluster load flow analysis is considered and pointed out, since it is the fundamental application for cluster management, e.g. optimization of the operating point of PC and SC. As the cluster philosophy results the traditional power systems in multi-level interconnected network, and it objects to operate based on each cluster area, the power system analysis must be adapted in order to support the flexible change of cluster system. Generally, the bus admittance matrix is used to define the system structure, and it is an essential element in every power systems analysis. If there is a change in grid e.g. the cluster restructuring, the consequence is a complex analysis regarding the complete recreation of the bus admittance matrix for the new system structure for the entire power systems. This reduces the flexibility of the cluster network. Furthermore, due to the network operator point of view, each cluster is allowed to receive only the connecting data from another cluster area. It means that the analysis has to be faced with this limitation as well.

To overcome those complexities in cluster analysis and forward separated operation target of the cluster philosophy, it must be declared that the analysis of interconnected clusters must be performed in a decoupling way. For example, there are three interconnected clusters networks, which are defined as superordinate, ordinate, and subordinate clusters. Assuming that ordinate cluster is currently taken into account and requested to execute load flow analysis. The voltage of interconnected nodes from superordinate and subordinate cluster must be included into the analysis of ordinate cluster. Because the voltage of interconnected nodes, which is one of system state variables, describes the character of other cluster areas. It can be noticed that the cluster analysis method has to deal with more than one voltage source, which does not occur in the typical power systems analysis. Hence, this research study contributes and proposes hybrid calculation technique as the strategy for cluster system analysis. This is because it provides the ability to solve the network containing mixing types of input sources, current sources and voltage sources. The character of hybrid calculation is applied and utilized as the main development technique of analysis algorithm. Even though, the hybrid technique is a well-known approach in linear algebra theory. It has never been applied to do either investigation or analysis in the power system.

Certainly, the cluster analysis strategy is figured out through the hybrid method, which supports the decoupled operation of cluster area. To complete the analysis algorithm, the target of clustering concept must be concerned. One target is to empower distribution network, for this reason, the asymmetrical analysis algorithm is evolved, because the character of distribution network is dominated by the unbalanced condition e.g. multi-phase feeder system. Moreover, the penetration of DG units can cause the unbalanced condition as well, e.g. single phase feed in of home PV systems. To deal with unbalanced condition, this research provides two analysis approaches, sequence hybrid and three-phase four-wire hybrid analysis method. Both proposed algorithms are developed based on different aspect. The sequence hybrid analysis method is pointed out to be a general method for the three-phase load flow study, which normally considers only phase values. The combination between sequence components and hybrid technique delivers a great benefit to separate three-phase system into three sequence networks. This means that the size of bus admittance matrix can be reduced by factor three, so the computational complexity is declined.

On the other hand, the three-phase four-wire hybrid method is further proposed to work with the system, in which the information of neutral cable is required, e.g., power quality analysis. Typically, the neutral wire in power flow study is merged into three-phase system, while the neutral wire current and voltage remains unknown. Due to this reason, the complete power flow algorithm for three-phase four-wire system base hybrid method is developed. This algorithm is able to solve the phase and neutral load flow problems. Unfortunately, it requires complete description of bus admittance matrix. Therefore, it takes obviously longer computational time, but less iteration steps than the sequence hybrid algorithm.

The validation case studies are given; the existing low voltage network and IEEE test feeders with asymmetrical load and generation. The DIgSilent PowerFactory and three-phase Newton-Raphson analysis method are used as reference. According to load flow results, small difference (20 mV) can be observed with DIgSilent PowerFactory program; this can be caused by the different network models or rather than the different buses admittance matrix. Meanwhile, the three-phase Newton-Raphson method, which utilized the same buses admittance matrix, delivers the identical results as proposed algorithms. This proves that both proposed algorithms are reliable and can function properly.

Moreover, the interconnected clusters case study is also illustrated. Three interconnected levels, superordinate, ordinate, and subordinate, are examined, where the ordinate level is considered as interested cluster area. Hence, the imported voltage from superordinate and subordinate cluster is compulsory to describe their character into ordinate cluster analysis. To assure the behavior of interconnected clusters network, the assumed situation is produced by the three-phase Newton-Raphson analysis method. Afterwards, both hybrid algorithms are executed, and are consequently able to represent the assumed situation. The results show that hybrid calculation technique can realize the target decoupled operation of clustering philosophy. The proposed hybrid analysis method is not only used for cluster analysis purpose, but it can also be utilized in the general power systems analysis.

To conclude, the major contribution of this research study is to provide the strategy for cluster management. Furthermore, the strategy must be simple and robust. Otherwise, the final outcome will be only the concept, and cannot be used in real power systems. This is the big challenge for the research. Hence, the hybrid approach is proposed and utilized as the calculation method of analysis algorithm. It is a simple method and delivers huge advantage in load flow analysis related to clustering power systems philosophy. The hybrid analysis algorithm is proposed through sequence hybrid and three-phase four-wire hybrid algorithm. Their usages can be limited by an interested issue of load flow study. The sequence hybrid algorithm cannot solve the study of three-phase four-wire network, but it is more suitable for a large network analysis than three-phase four-wire hybrid algorithm. Nonetheless, it is noteworthy to state that both algorithms give the same load flow results under the identical load flow study. All in all, the proposed hybrid analysis is ready to be the main function to execute optimization and management process of cluster systems as well as the supervisory of automated cluster control application. Last but not least, it ensures and forwards the development of clustering power systems philosophy to be one solution of sustainable energy supply systems.

8.2 Future Works

This research study is particularly proposed the strategy for cluster analysis, which forwards and dives the development of clustering power systems philosophy. Furthermore, the introduced analysis method is basically evolved to deal with the asymmetrical condition. Obviously, further investigation and development based on cluster approach is absolutely important in order to realize a smart supply system. Further research areas are stated in the following as well as the concerned condition of future development.

Since, the cluster analysis based on hybrid calculation technique is done, the other management application can be executed e.g. the load and power generation forecasting. Accordingly, the market model based clustering concept can be stepwise evolved and realized as well.

Consequently, it must be foreseen that the massive information and the measurement data are directly growing up along the improvement of intelligent network. It is definitely a critical issue of the future power systems as well as the clustering power system. Therefore, a clear organization of cluster concept must be figured out for the data management and organization. The database technique, which has been globally used to handle and process with the massive information, has to come up as data storages for modern power systems.

Regarding the mentioned issue of future works, it is expected that the continuation and the data management of clustering philosophy is still required. It can be guaranteed that clustering philosophy is able to fulfill and realize the future grid.

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Appendix

Besides the development of hybrid load flow algorithms, which are presented in Chapter 6, it is also essential to figure out how to describe power systems network or rather to create buses admittance matrix. Therefore, a mathematical model of power systems network elements, i.e. transformer and cable, is elucidated in the first section. Obviously, the mathematical model is presented based on the three-phase system and the three-phase four-wire system. The second section shows the parameters of network elements which are utilized in verification case studies in Chapter7, as well as, the unbalanced conditions of power generation and load.

A.1 Power Systems Network Element Models

Regards the accuracy in power flow solution, a key issue is relied on the power systems elements model. Hence, the mathematical description of important power system elements, e.g. distribution transformer and cable, are explained in this appendix section. The models are described and explained based on sequence components, three-phase system, and three-phase four-wire system. In addition, a creation of buses admittance matrix is also pointed out.

A.1.1 Three-Phase Transformer Model

To describe a mathematical model of three-phase transformer, the sequence components are selected for the explanation, since the transformer in this thesis is considered as symmetrical. Typically, a positive and negative sequence transformer model is presented with the same equivalent model. On the other hand, a zero sequence model is different regarding a vector group. In order to obtain transformer admittance matrix, necessary parameters and equation are listed at the end of this section.

A.1.1.1 Positive and Negative Sequence Transformer Model

As the positive and the negative sequences of any three-phase transformer are represented by the same sequence equivalent circuit, thus, a general equivalent circuit of positive sequence for any vector group is shown in Fig. A.1. Where, index P is stated for primary side, index S is for secondary side.

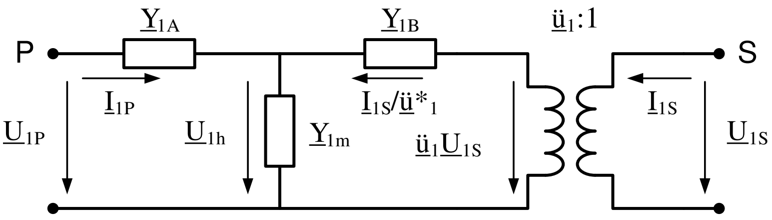

Fig. A.1: Positive sequence transformer T-equivalent circuit [4]

According to the presented equivalent circuit, the node admittance matrix based on primary side can be written as in Eq. (A.1).

$$\begin{bmatrix} \underline{I}_{1P} \\ \underline{\ddot{u}}_1^{*-1}\underline{I}_{1S} \\ 0 \end{bmatrix} = \begin{bmatrix} \underline{Y}_{1A} & 0 & -\underline{Y}_{1A} \\ 0 & \underline{Y}_{1B} & -\underline{Y}_{1B} \\ -\underline{Y}_{1A} & -\underline{Y}_{1B} & \underline{Y}_{1A}+\underline{Y}_{1B}+\underline{Y}_{1m} \end{bmatrix} \begin{bmatrix} \underline{U}_{1P} \\ \underline{\ddot{u}}_1\underline{U}_{1S} \\ \underline{U}_{1h} \end{bmatrix} \tag{A.1}$$

To obtain the matrix in general form of two-port system, the matrix dimension of Eq. (A.1) has to be reduced to 2×2. Therefore, the magnetic field voltage ($\underline{U}_{1h}$) has to be eliminated. Regarding Kirchhoff's current law, $\underline{U}_{1h}$ can be written as

$$\underline{U}_{1h} = \frac{\underline{Y}_{1A}\underline{U}_{1P} + \underline{\ddot{u}}_1\underline{Y}_{1B}\underline{U}_{1S}}{\underline{Y}_{1A}+\underline{Y}_{1B}+\underline{Y}_{1m}} \tag{A.2}$$

Replacing $\underline{U}_{1h}$ in Eq. (A.1), then the two-port system can be derived as

$$\begin{bmatrix} \underline{I}_{1P} \\ \underline{I}_{1S} \end{bmatrix} = \frac{1}{\underline{Y}_{1A}+\underline{Y}_{1B}+\underline{Y}_{1m}} \begin{bmatrix} \underline{Y}_{1A}\underline{Y}_{1B}+\underline{Y}_{1A}\underline{Y}_{1m} & -\underline{\ddot{u}}_1\underline{Y}_{1A}\underline{Y}_{1B} \\ -\underline{\ddot{u}}_1^{*}\underline{Y}_{1A}\underline{Y}_{1B} & \left|\underline{\ddot{u}}_1\right|^2(\underline{Y}_{1A}\underline{Y}_{1B}+\underline{Y}_{1A}\underline{Y}_{1m}) \end{bmatrix} \begin{bmatrix} \underline{U}_{1P} \\ \underline{U}_{1S} \end{bmatrix} \tag{A.3}$$

Eq. (A.3) is the positive sequence transformer matrix. Since the negative sequence can be represented with the same equivalent circuit, the negative sequence transformer matrix is consequently resulted in the same form as below

$$\begin{bmatrix} \underline{I}_{2P} \\ \underline{I}_{2S} \end{bmatrix} = \frac{1}{\underline{Y}_{2A}+\underline{Y}_{2B}+\underline{Y}_{2m}} \begin{bmatrix} \underline{Y}_{2A}\underline{Y}_{2B}+\underline{Y}_{2A}\underline{Y}_{2m} & -\underline{\ddot{u}}_2\underline{Y}_{2A}\underline{Y}_{2B} \\ -\underline{\ddot{u}}_2^{*}\underline{Y}_{2A}\underline{Y}_{2B} & \left|\underline{\ddot{u}}_2\right|^2(\underline{Y}_{2A}\underline{Y}_{2B}+\underline{Y}_{2A}\underline{Y}_{2m}) \end{bmatrix} \begin{bmatrix} \underline{U}_{2P} \\ \underline{U}_{2S} \end{bmatrix} \tag{A.4}$$

It is noteworthy to mention that the positive and negative sequence transformer models are able to describe for every vector group. In order to identify an effect of vector group, the zero sequence model is discussed in the next section.

A.1.1.2 Zero Sequence Transformer Model

As mentioned, a key element to differentiate transformer vector group is the zero sequence, since the zero sequence networks are commonly utilized to define ground connection. Moreover, it can also describe the transformer core structure and vector group connection. Therefore, the zero sequence equivalent model of each vector group is introduced and summarized in order to figure out the node admittance matrix.

To categorize vector group, an identification letter is illustrated in Table A.1. A capital letter identifies the winding group on the primary side; lowercase letter is for the winding group on the secondary side.

Table A.1: Identification letter for transformer vector group

Winding	Delta	Star	Zigzag	Grounding
Primary side	D	Y	Z	N
Secondary side	d	y	z	n

Vector group YNyn:

In case of group YNyn, the zero sequence equivalent circuit is identical with the positive sequence equivalent circuit, because the primary side and the secondary side are linked through grounding. The ground impedances ($\underline{Z}_M$) are added to both sides with factor three, as shown in Fig. A.2.

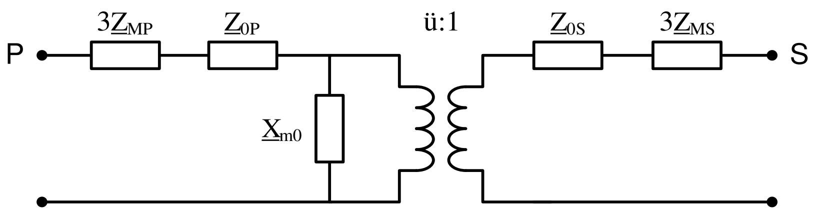

Fig. A.2: Zero sequence transformer equivalent circuit – YNyn

Consequently, the equivalent circuit zero sequence network of YNyn group can be simplified by T-equivalent circuit, as presented in Fig. A.3, where the grounding impedance of primary side and secondary side are included in $\underline{Y}_{0A}$ and $\underline{Y}_{0B}$, respectively.

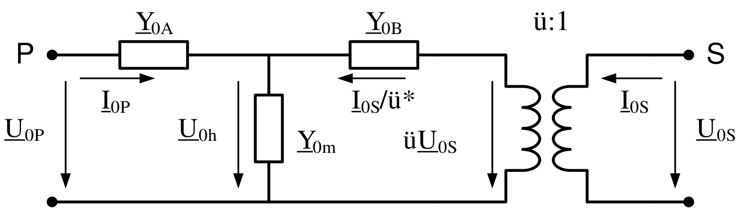

Fig. A.3: Zero sequence transformer T-equivalent circuit – YNyn

As a direct result, the node impedance matrix can be written as

$$\begin{bmatrix}\underline{I}_{0P}\\ \underline{I}_{0S}\end{bmatrix}=\frac{1}{\underline{Y}_{0A}+\underline{Y}_{0B}+\underline{Y}_{0m}}\begin{bmatrix}\underline{Y}_{0A}\underline{Y}_{0B}+\underline{Y}_{0A}\underline{Y}_{0m} & -ü\,\underline{Y}_{0A}\underline{Y}_{0B}\\ -ü^*\underline{Y}_{0A}\underline{Y}_{0B} & |ü|^2(\underline{Y}_{0A}\underline{Y}_{0B}+\underline{Y}_{0A}\underline{Y}_{0m})\end{bmatrix}\begin{bmatrix}\underline{U}_{0P}\\ \underline{U}_{0S}\end{bmatrix} \tag{A.5}$$

Vector group YNd:

In this vector group, the grounding impedance is only available on star side. Clearly, the delta side is described with open circuit. Therefore, the zero sequence equivalent of Ynd group is portrayed in Fig. A.4, where all impedance is based on primary side.

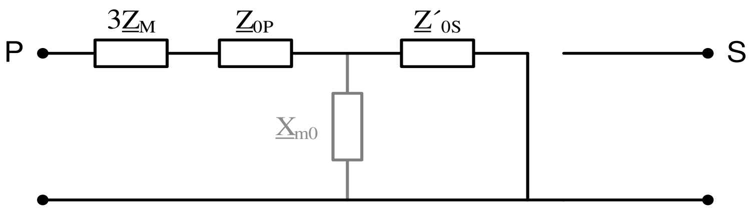

Fig. A.4: Zero sequence transformer equivalent circuit – YNd

Regarding the equivalent circuit, the zero sequence admittance matrix of vector group Ynd can be received in Eq. (A.6).

$$\begin{bmatrix}\underline{I}_{0P}\\ \underline{I}_{0S}\end{bmatrix}=\begin{bmatrix}\dfrac{\underline{Y}_{0A}\underline{Y}_{0B}+\underline{Y}_{0A}\underline{Y}_{0m}}{\underline{Y}_{0A}+\underline{Y}_{0B}+\underline{Y}_{0m}} & 0\\ 0 & 0\end{bmatrix}\begin{bmatrix}\underline{U}_{0P}\\ \underline{U}_{0S}\end{bmatrix} \tag{A.6}$$

Commonly in case of delta winding, the zero sequence magnetizing impedance is concerned as very large impedance, due to transformer core structure and connections. Hence, the zero sequence magnetizing impedance can be neglected. The zero sequence admittance matrix of transformer vector group Ynd can be simplified as

$$\begin{bmatrix} \underline{I}_{0P} \\ \underline{I}_{0S} \end{bmatrix} = \begin{bmatrix} \dfrac{1}{\underline{Z}_0 + 3\underline{Z}_M} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \underline{U}_{0P} \\ \underline{U}_{0S} \end{bmatrix} \tag{A.7}$$

Vector group Dyn:

It is understandable that the zero sequence equivalent circuit of vector group Dyn can be inversely presented by vector group YNd, and hence the zero sequence equivalent of Dyn group is shown in Fig. A.5. Since the ground impedance is existed on star side, thus, all impedance is described based on secondary side.

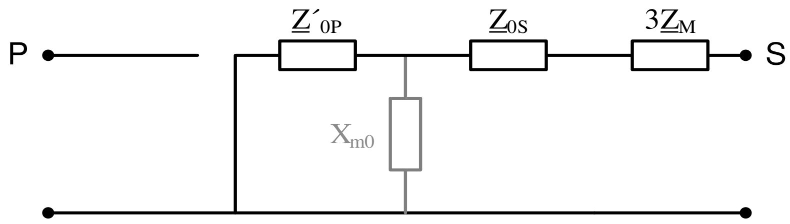

Fig. A.5: Zero sequence transformer equivalent circuit – Dyn

As a direct result, the zero sequence admittance matrix can be obtained as

$$\begin{bmatrix} \underline{I}_{0P} \\ \underline{I}_{0S} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \dfrac{ü^2\left(\underline{Y}_{0A}\underline{Y}_{0B} + \underline{Y}_{0A}\underline{Y}_{0m}\right)}{\underline{Y}_{0A} + \underline{Y}_{0B} + \underline{Y}_{0m}} \end{bmatrix} \begin{bmatrix} \underline{U}_{0P} \\ \underline{U}_{0S} \end{bmatrix} \tag{A.8}$$

Similarly, the zero sequence magnetizing impedance for delta winding can be ignored because it is very large impedance. The zero sequence admittance matrix of vector group Dyn, therefore, can be simplified as

$$\begin{bmatrix} \underline{I}_{0P} \\ \underline{I}_{0S} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \dfrac{1}{\underline{Z}_0 + 3\underline{Z}_M} \end{bmatrix} \begin{bmatrix} \underline{U}_{0P} \\ \underline{U}_{0S} \end{bmatrix} \tag{A.9}$$

Vector group YNzn:

The zero sequence equivalent circuit of YNzn group is shown in Fig. A.6, in which ground impedances are placed on both sides.

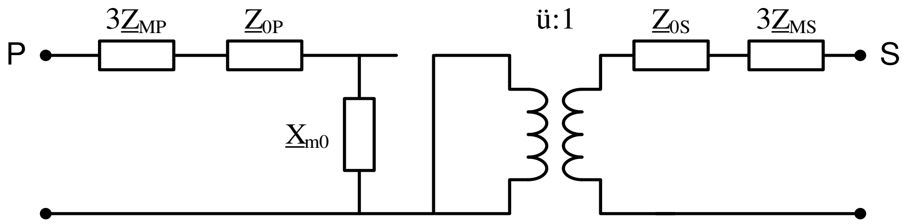

Fig. A.6: Zero sequence transformer equivalent circuit – YNzn

It is noticeable that both side of transformer are decoupled. Then, the zero sequence admittance matrix can be easily obtained as following:

$$\begin{bmatrix} \underline{I}_{0P} \\ \underline{I}_{0S} \end{bmatrix} = \begin{bmatrix} \dfrac{1}{(\underline{Z}_{0P} + j\underline{X}_{M0} + 3\underline{Z}_{MP})} & 0 \\ 0 & \dfrac{1}{(\underline{Z}_{0S} + 3\underline{Z}_{MS})} \end{bmatrix} \begin{bmatrix} \underline{U}_{0P} \\ \underline{U}_{0S} \end{bmatrix} \tag{A.10}$$

A.1.1.3 Admittance matrix of Three-Phase Transformer

Up to this point, the admittance matrix of each transformer vector group is presented trough sequence components. In order to obtain admittance matrix of three-phase transformer, a general form of sequence admittance matrix is firstly taken into account, as illustrated in Eq. (A.11), where index S is stated for the sequence components.

$$\begin{bmatrix} \underline{I}_{SP} \\ \underline{I}_{SS} \end{bmatrix} = \begin{bmatrix} \underline{Y}_{SAA} & \underline{Y}_{SAB} \\ \underline{Y}_{SBA} & \underline{Y}_{SBB} \end{bmatrix} \begin{bmatrix} \underline{U}_{SP} \\ \underline{U}_{SS} \end{bmatrix} \tag{A.11}$$

Consequently, the transformer admittance matrix of all sequence can be expressed as shown in Eq. (A.12).

$$\begin{bmatrix} \underline{I}_{1P} \\ \underline{I}_{2P} \\ \underline{I}_{0P} \\ \underline{I}_{1S} \\ \underline{I}_{2S} \\ \underline{I}_{0S} \end{bmatrix} = \begin{bmatrix} \underline{Y}_{1AA} & 0 & 0 & \underline{Y}_{1AB} & 0 & 0 \\ 0 & \underline{Y}_{2AA} & 0 & 0 & \underline{Y}_{2AB} & 0 \\ 0 & 0 & \underline{Y}_{0AA} & 0 & 0 & \underline{Y}_{0AB} \\ \underline{Y}_{1BA} & 0 & 0 & \underline{Y}_{1BB} & 0 & 0 \\ 0 & \underline{Y}_{2BA} & 0 & 0 & \underline{Y}_{2BB} & 0 \\ 0 & 0 & \underline{Y}_{0BA} & 0 & 0 & \underline{Y}_{0BB} \end{bmatrix} \begin{bmatrix} \underline{U}_{1P} \\ \underline{U}_{2P} \\ \underline{U}_{0P} \\ \underline{U}_{1S} \\ \underline{U}_{2S} \\ \underline{U}_{0S} \end{bmatrix} \tag{A.12}$$

By transforming sequence components to phase systems, the admittance matrix of three-phase transformer is obtained and described in phase system as in Eq. (A.13).

$$\begin{bmatrix} \underline{I}_{aP} \\ \underline{I}_{bP} \\ \underline{I}_{cP} \\ \underline{I}_{aS} \\ \underline{I}_{bS} \\ \underline{I}_{cS} \end{bmatrix} = \begin{bmatrix} \underline{Y}_{aa,AA} & \underline{Y}_{ab,AA} & \underline{Y}_{ac,AA} & \underline{Y}_{aa,AB} & \underline{Y}_{ab,AB} & \underline{Y}_{ac,AB} \\ \underline{Y}_{ba,AA} & \underline{Y}_{bb,AA} & \underline{Y}_{bc,AA} & \underline{Y}_{ba,AB} & \underline{Y}_{bb,AB} & \underline{Y}_{bc,AB} \\ \underline{Y}_{ca,AA} & \underline{Y}_{cb,AA} & \underline{Y}_{cc,AA} & \underline{Y}_{ca,AB} & \underline{Y}_{cb,AB} & \underline{Y}_{cc,AB} \\ \underline{Y}_{aa,BA} & \underline{Y}_{ab,BA} & \underline{Y}_{ac,BA} & \underline{Y}_{aa,BB} & \underline{Y}_{ab,BB} & \underline{Y}_{ac,BB} \\ \underline{Y}_{ba,BA} & \underline{Y}_{bb,BA} & \underline{Y}_{bc,BA} & \underline{Y}_{ba,BB} & \underline{Y}_{bb,BB} & \underline{Y}_{bc,BB} \\ \underline{Y}_{ac,BA} & \underline{Y}_{bc,BA} & \underline{Y}_{cc,BA} & \underline{Y}_{ca,BB} & \underline{Y}_{cb,BB} & \underline{Y}_{cc,BB} \end{bmatrix} \begin{bmatrix} \underline{U}_{aP} \\ \underline{U}_{bP} \\ \underline{U}_{cP} \\ \underline{U}_{aS} \\ \underline{U}_{bS} \\ \underline{U}_{cS} \end{bmatrix} \tag{A.13}$$

It is noteworthy to mention that the current three-phase transformer model or rather bus admittance matrix can be only used in three-phase system analysis. If the analysis of neutral cable is of interest, the transformer model has to expand in order to describe the character of neutral cable. The expansion of three-phase transformer model is explained in the next section.

A.1.2 Three-Phase Four-Wire Transformer Model

The expansion of three-phase transformer model is needed, when the analysis of three-phase four-wire power systems is of interest. The availability of neutral cable results in the increasing of transformer bus admittance matrix dimension from 6×6 to 8×8. An explanation of matrix expansion can be divided into two parts regarding a neutral connection of transformer star point; with- and without neutral connection.

Firstly, the without neutral connection case is considered. To give an overview and to demonstrate bus admittance matrix of this case, the Dyn transformer is selected for the explanation. Fig. A.7 shows the connection overview of Dyn transformer, where the neutral terminal is not connected to star point.

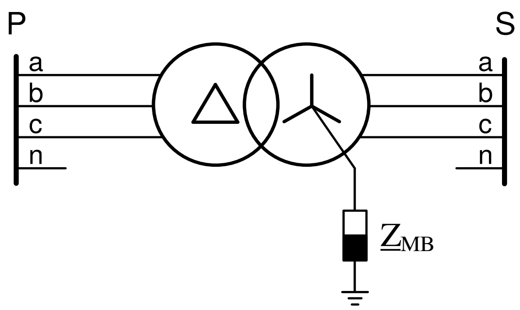

Fig. A.7: Dyn transformer without neutral connection at star point

In fact, this kind of transformer configuration is represented in the three-phase systems. Therefore, the three-phase transform bus admittance matrix, shown in Eq. (A.13), can be directly expanded; the neutral position in bus admittance matrix is replaced with zero value, as illustrated in Eq. (A.14). This can be done because the neutral terminal voltage is commonly set to zero or grounded.

$$\begin{bmatrix} \underline{I}_{aP} \\ \underline{I}_{bP} \\ \underline{I}_{cP} \\ \underline{I}_{nP} \\ \underline{I}_{aS} \\ \underline{I}_{bS} \\ \underline{I}_{cS} \\ \underline{I}_{nS} \end{bmatrix} = \begin{bmatrix} \underline{Y}_{aa,AA} & \underline{Y}_{ab,AA} & \underline{Y}_{ac,AA} & 0 & \underline{Y}_{aa,AB} & \underline{Y}_{ab,AB} & \underline{Y}_{ac,AB} & 0 \\ \underline{Y}_{ba,AA} & \underline{Y}_{bb,AA} & \underline{Y}_{bc,AA} & 0 & \underline{Y}_{ba,AB} & \underline{Y}_{bb,AB} & \underline{Y}_{bc,AB} & 0 \\ \underline{Y}_{ca,AA} & \underline{Y}_{cb,AA} & \underline{Y}_{cc,AA} & 0 & \underline{Y}_{ca,AB} & \underline{Y}_{cb,AB} & \underline{Y}_{cc,AB} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \underline{Y}_{aa,BA} & \underline{Y}_{ab,BA} & \underline{Y}_{ac,BA} & 0 & \underline{Y}_{aa,BB} & \underline{Y}_{ab,BB} & \underline{Y}_{ac,BB} & 0 \\ \underline{Y}_{ba,BA} & \underline{Y}_{bb,BA} & \underline{Y}_{bc,BA} & 0 & \underline{Y}_{ba,BB} & \underline{Y}_{bb,BB} & \underline{Y}_{bc,BB} & 0 \\ \underline{Y}_{ac,BA} & \underline{Y}_{bc,BA} & \underline{Y}_{cc,BA} & 0 & \underline{Y}_{ca,BB} & \underline{Y}_{cb,BB} & \underline{Y}_{cc,BB} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \underline{U}_{aP} \\ \underline{U}_{bP} \\ \underline{U}_{cP} \\ \underline{U}_{nP} \\ \underline{U}_{aS} \\ \underline{U}_{bS} \\ \underline{U}_{cS} \\ \underline{U}_{nS} \end{bmatrix} \tag{A.14}$$

Secondly, the neutral terminal is connected to the transformer star point. Fig. A.8 portrays a connection overview based on Dyn transformer.

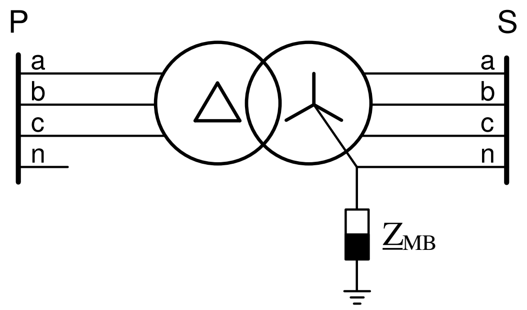

Fig. A.8: Dyn transformer with neutral connection at star point

If this transformer configuration is concerned as three-phase system, it can be understood that the reference point of the secondary side is the neutral terminal. Thus, Eq. (A.13) can be rewritten as in Eq. (A.15). Noticeably, the neutral terminal voltage is concerned only on the secondary side, since it is connected with transformer star point.

$$\begin{bmatrix} \underline{I}_{aP} \\ \underline{I}_{bP} \\ \underline{I}_{cP} \\ \underline{I}_{aS} \\ \underline{I}_{bS} \\ \underline{I}_{cS} \end{bmatrix} = \begin{bmatrix} \underline{Y}_{aa,AA} & \underline{Y}_{ab,AA} & \underline{Y}_{ac,AA} & \underline{Y}_{aa,AB} & \underline{Y}_{ab,AB} & \underline{Y}_{ac,AB} \\ \underline{Y}_{ba,AA} & \underline{Y}_{bb,AA} & \underline{Y}_{bc,AA} & \underline{Y}_{ba,AB} & \underline{Y}_{bb,AB} & \underline{Y}_{bc,AB} \\ \underline{Y}_{ca,AA} & \underline{Y}_{cb,AA} & \underline{Y}_{cc,AA} & \underline{Y}_{ca,AB} & \underline{Y}_{cb,AB} & \underline{Y}_{cc,AB} \\ \underline{Y}_{aa,BA} & \underline{Y}_{ab,BA} & \underline{Y}_{ac,BA} & \underline{Y}_{aa,BB} & \underline{Y}_{ab,BB} & \underline{Y}_{ac,BB} \\ \underline{Y}_{ba,BA} & \underline{Y}_{bb,BA} & \underline{Y}_{bc,BA} & \underline{Y}_{ba,BB} & \underline{Y}_{bb,BB} & \underline{Y}_{bc,BB} \\ \underline{Y}_{ac,BA} & \underline{Y}_{bc,BA} & \underline{Y}_{cc,BA} & \underline{Y}_{ca,BB} & \underline{Y}_{cb,BB} & \underline{Y}_{cc,BB} \end{bmatrix} \begin{bmatrix} \underline{U}_{aP} \\ \underline{U}_{bP} \\ \underline{U}_{cP} \\ \underline{U}_{aS} - \underline{U}_{nS} \\ \underline{U}_{bS} - \underline{U}_{nS} \\ \underline{U}_{cS} - \underline{U}_{nS} \end{bmatrix} \tag{A.15}$$

To expand Eq. (A.15) for three-phase four-wire system, the neutral terminal voltage must be extracted and the reference point of the network is set to earth system. Consequently, Eq. (A.15) can be obtained as following

$$\begin{bmatrix} \underline{I}_{aP} \\ \underline{I}_{bP} \\ \underline{I}_{cP} \\ \underline{I}_{nP} \\ \underline{I}_{aS} \\ \underline{I}_{bS} \\ \underline{I}_{cS} \\ \underline{I}_{nS} \end{bmatrix} = \begin{bmatrix} \underline{Y}_{aa,AA} & \underline{Y}_{ab,AA} & \underline{Y}_{ac,AA} & 0 & \underline{Y}_{aa,AB} & \underline{Y}_{ab,AB} & \underline{Y}_{ac,AB} & \underline{Y}_{an,AB} \\ \underline{Y}_{ba,AA} & \underline{Y}_{bb,AA} & \underline{Y}_{bc,AA} & 0 & \underline{Y}_{ba,AB} & \underline{Y}_{bb,AB} & \underline{Y}_{bc,AB} & \underline{Y}_{bn,AB} \\ \underline{Y}_{ca,AA} & \underline{Y}_{cb,AA} & \underline{Y}_{cc,AA} & 0 & \underline{Y}_{ca,AB} & \underline{Y}_{cb,AB} & \underline{Y}_{cc,AB} & \underline{Y}_{cn,AB} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \underline{Y}_{aa,BA} & \underline{Y}_{ab,BA} & \underline{Y}_{ac,BA} & 0 & \underline{Y}_{aa,BB} & \underline{Y}_{ab,BB} & \underline{Y}_{ac,BB} & \underline{Y}_{an,BB} \\ \underline{Y}_{ba,BA} & \underline{Y}_{bb,BA} & \underline{Y}_{bc,BA} & 0 & \underline{Y}_{ba,BB} & \underline{Y}_{bb,BB} & \underline{Y}_{bc,BB} & \underline{Y}_{bn,BB} \\ \underline{Y}_{ac,BA} & \underline{Y}_{bc,BA} & \underline{Y}_{cc,BA} & 0 & \underline{Y}_{ca,BB} & \underline{Y}_{cb,BB} & \underline{Y}_{cc,BB} & \underline{Y}_{cn,BB} \\ \underline{Y}_{na,BA} & \underline{Y}_{nb,BA} & \underline{Y}_{nc,BA} & 0 & \underline{Y}_{na,BB} & \underline{Y}_{nb,BB} & \underline{Y}_{nc,BB} & \underline{Y}_{nn,BB} \end{bmatrix} \begin{bmatrix} \underline{U}_{aP} \\ \underline{U}_{bP} \\ \underline{U}_{cP} \\ \underline{U}_{nP} \\ \underline{U}_{aS} \\ \underline{U}_{bS} \\ \underline{U}_{cS} \\ \underline{U}_{nS} \end{bmatrix} \tag{A.16}$$

Clearly, the admittance values relate to neutral terminal at primary side are zero, since the neutral voltage at the primary side or rather delta side ($\underline{U}_{nP}$) is not existed. To complete bus admittance matrix, the admittance values related to neutral terminal at the secondary side have to be calculated. In order to figure out, the mutual admittance between nodes a and n ($\underline{Y}_{an,BB}$) and the self-admittance of node n ($\underline{Y}_{nn,BB}$) on secondary side are selected for elucidation.

Finding the mutual admittance between nodes a and n ($\underline{Y}_{an,BB}$), the phase a current of the secondary side in Eq. (A.15) is considered. As a result, it can be written as in Eq. (A.17).

$$\underline{I}_{aS} = \begin{bmatrix} \underline{Y}_{aa,BA} & \underline{Y}_{ab,BA} & \underline{Y}_{ac,BA} \end{bmatrix} \begin{bmatrix} \underline{U}_{aP} \\ \underline{U}_{bP} \\ \underline{U}_{cP} \end{bmatrix} + \begin{bmatrix} \underline{Y}_{aa,BB} & \underline{Y}_{ab,BB} & \underline{Y}_{ac,BB} \end{bmatrix} \begin{bmatrix} \underline{U}_{aS} - \underline{U}_{nS} \\ \underline{U}_{bS} - \underline{U}_{nS} \\ \underline{U}_{cS} - \underline{U}_{nS} \end{bmatrix} \tag{A.17}$$

Observing the effect of the neutral voltage at secondary side ($\underline{U}_{nS}$) on admittance values, it found that the mutual admittance between nodes a and n ($\underline{Y}_{an,BB}$) is the negative summation of admittance values in

$$\underline{Y}_{an,BB} = -\left(\underline{Y}_{aa,BB} + \underline{Y}_{ab,BB} + \underline{Y}_{ab,BB}\right) \tag{A.18}$$

Logically, the mutual admittance between nodes b and n, and between nodes c and n can be derived in the identical way. As all the mutual admittances are calculated, next, the self-admittance of node n ($\underline{Y}_{nn,BB}$) is examined. To find the self-admittance, the neutral current of secondary side ($\underline{I}_{nS}$) is concerned. Regarding Fig. A.8, the $\underline{I}_{nS}$ can be obtain as in Eq. (A.19).

$$\underline{I}_{nS} = -\left(\underline{I}_{aS} + \underline{I}_{bS} + \underline{I}_{cS}\right) + \underline{Y}_{MB}\underline{U}_{nS} \tag{A.19}$$

According to Eq. (A.16), the secondary side current of phase a, b, and c can be subsequently received as

$$\begin{bmatrix} \underline{I}_{aS} \\ \underline{I}_{bS} \\ \underline{I}_{cS} \end{bmatrix} = \begin{bmatrix} \underline{Y}_{aa,BA} & \underline{Y}_{ab,BA} & \underline{Y}_{ac,BA} \\ \underline{Y}_{ba,BA} & \underline{Y}_{bb,BA} & \underline{Y}_{bc,BA} \\ \underline{Y}_{ac,BA} & \underline{Y}_{bc,BA} & \underline{Y}_{cc,BA} \end{bmatrix} \begin{bmatrix} \underline{U}_{aP} \\ \underline{U}_{bP} \\ \underline{U}_{cP} \end{bmatrix} + \begin{bmatrix} \underline{Y}_{aa,BB} & \underline{Y}_{ab,BB} & \underline{Y}_{ac,BB} & \underline{Y}_{an,BB} \\ \underline{Y}_{ba,BB} & \underline{Y}_{bb,BB} & \underline{Y}_{bc,BB} & \underline{Y}_{bn,BB} \\ \underline{Y}_{ca,BB} & \underline{Y}_{cb,BB} & \underline{Y}_{cc,BB} & \underline{Y}_{cn,BB} \end{bmatrix} \begin{bmatrix} \underline{U}_{aS} \\ \underline{U}_{bS} \\ \underline{U}_{cS} \\ \underline{U}_{nS} \end{bmatrix} \qquad (A.20)$$

After summing all three currents and combining with Eq. (A.19), the self-admittance of node n ($\underline{Y}_{nn,BB}$) is resulted in

$$\underline{Y}_{nn,BB} = -\left(\underline{Y}_{an,BB} + \underline{Y}_{bn,BB} + \underline{Y}_{cn,BB}\right) + \underline{Y}_{MB} \qquad (A.21)$$

It must be noted that the recent calculation method of the mutual admittance and the self-admittance, which are related to neutral cable, are explained based on transformer secondary side. Even though, it can be utilized for the calculation on the primary side as well.

So far, the expansion of three-phase four-wire transformer bus admittance matrix is complete. However, a grounding configuration is worth a discussion. Fig. A.9 shows two types of grounding, solid-earthed neutral configuration and unearthed neutral configuration. Those have a direct effect to the calculation of the self-admittance of node n. In case of solid-earthed neutral configuration, the earthing admittance value ($\underline{Y}_{MB}$) is equal to zero, since it is shorted-circuit to ground system. This means that $\underline{Y}_{nn,BB}$ remains only on the part of the mutual admittance summation, as noticed in Eq. (A.21).

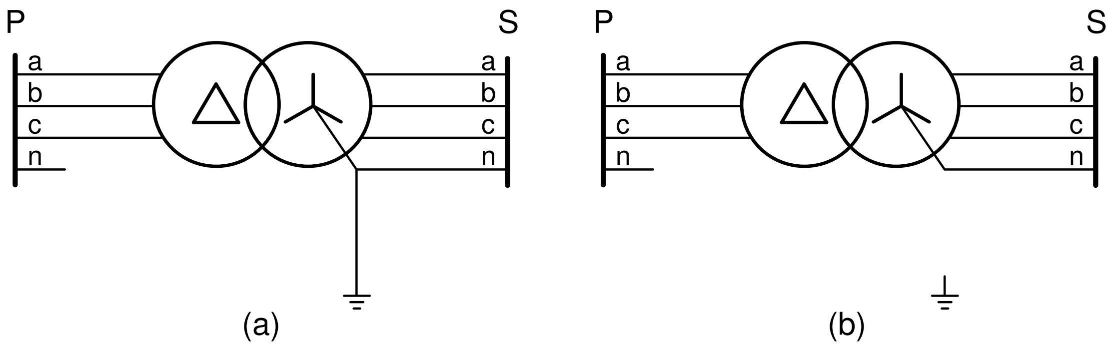

Fig. A.9: (a) Solid-earthed neutral configuration, (b) Unearthed neutral configuration

On the other hand, the unearthed neutral configuration can be implied as open-circuit. Therefore, $\underline{Y}_{MB}$ is equal to infinity. As a consequence, the self-admittance of node n $\underline{Y}_{nn,BB}$ is resulted in an infinity value. In the next section, a parameter calculation of three-phase transformer model is elucidated.

A.1.3 Three-Phase Transformer Parameter Calculation

Before having a look on parameter calculation, it must be mentioned that this section is summarized from DIgSilient's transformer description [154]. In order to obtain the admittance matrix of three-phase transformer, the estimated parameter of transformer must be firstly calculated from the technical data. To simplify the calculation, the parameters are described based on per unit value. In addition, the transformer equivalent circuit in per unit value is illustrated in Fig. A.10.

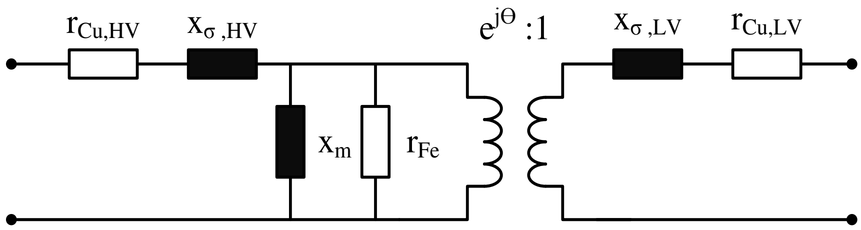

Fig. A.10: Transformer equivalent circuit in pu. [154]

Since the model is described in per unit value, it is noteworthy to defined base impedance of primary side and secondary side. Their base impedances are shown on Eq. (A.22) and Eq. (A.23), respectively.

$$Z_{r,HV} = \frac{U_{r,HV}^{2}}{S_r} \tag{A.22}$$

$$Z_{r,LV} = \frac{U_{r,LV}^{2}}{S_r} \tag{A.23}$$

In the following, the calculation of transformer impedance is separated into two parts: primary and secondary impedance, and magnetization impedance part. All parameters descriptions are detailed on Table A.2.

Primary and secondary impedance in pu.

$$z_{SC} = \frac{u_{SC}}{100} \tag{A.24}$$

$$r_{SC} = \frac{P_{Cu}/1000}{S_r} \tag{A.25}$$

$$x_{SC} = \sqrt{z_{SC}^2 - r_{SC}^2} \tag{A.26}$$

$$r_{Cu,HV} = s_{R,HV} \cdot r_{SC} \tag{A.27}$$

$$r_{Cu,LV} = (1 - s_{R,HV}) \cdot r_{SC} \tag{A.28}$$

$$x_{\sigma,HV} = s_{X,HV} \cdot x_{SC} \tag{A.29}$$

$$x_{\sigma,LV} = (1 - s_{X,HV}) \cdot x_{SC} \tag{A.30}$$

Magnetizing impedance in pu.

$$z_M = \frac{100}{I_{mg}} \tag{A.31}$$

$$r_{Fe} = \frac{S_r}{P_{Fe} / 1000} \tag{A.32}$$

$$x_M = \frac{1}{\sqrt{\frac{1}{z_M^2} - \frac{1}{r_{Fe}^2}}} \tag{A.33}$$

Table A.2: Transformer parameter description

Parameter	**Description**	**Unit**
$Z_{r,HV}$	Nominal impedance high voltage side	[Ω]
$Z_{r,LV}$	Nominal impedance low voltage side	[Ω]
Urh	Rated voltage of high side voltage	[kV]
Url	Rated voltage of low side voltage	[kV]
Sr	Rated power	[MVA]
ph	Phase shift	[x*30°]
P_{Cu}	Copper loss	[kW]
usc	Short circuit voltage	[%]
zsc	Short circuit impedance	[pu.]
rsc	Short circuit resistance	[pu.]
xsc	Short circuit reactance	[pu.]
sRh	Share of short circuit resistance on high side	[pu.]
sXh	Share of short circuit reactance on high side	[pu.]
$r_{Cu,HV}$, $r_{Cu,LV}$	Resistance on HV/LV side	[pu.]
$x_{\sigma,HV}$, $x_{\sigma,LV}$	Leakage reactance on HV/LV side	[pu.]
Img	No load circuit current	[%]

P_{Fe}	No load loss	[kW]
X_M	Magnetizing impedance	[pu.]
r_{Fe}	Shunt resistance	[pu.]

A.1.4 Cable Model

Mostly in distribution network, the three-phase four-wire cable is commonly used. Fig. A.11 shows the general model of three-phase four-wire, where $\underline{Z}_{mm}$ is self-impedance of each cable and $\underline{Z}_{mn}$ is mutual impedance between each cable. As an obvious result, the mathematical description or bus admittance matrix of this cable type is resulted to 4×4 matrix dimension. This cable description can be directly utilized in the three-phase four-wire hybrid load flow algorithm.

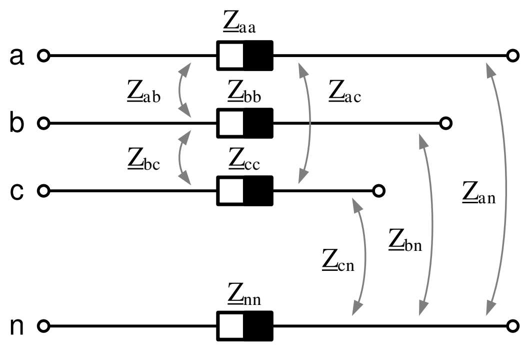

Fig. A.11: Three-phase four-wire cable

But, for the usage in sequence hybrid analysis, one matrix dimension of the three-phase four-wire cable must be reduced in order to transform to sequence components. This can be done by integrating the effect of neutral line into phase 'abc' system. To figure out the reducing process, the general equation of three-phase four-wire system is firstly examined.

$$\begin{bmatrix} \underline{U}_a \\ \underline{U}_b \\ \underline{U}_c \\ \underline{U}_n \end{bmatrix} = \begin{bmatrix} \underline{Z}_{aa} & \underline{Z}_{ab} & \underline{Z}_{ac} & \underline{Z}_{an} \\ \underline{Z}_{ab} & \underline{Z}_{bb} & \underline{Z}_{bc} & \underline{Z}_{bn} \\ \underline{Z}_{ac} & \underline{Z}_{bc} & \underline{Z}_{cc} & \underline{Z}_{cn} \\ \underline{Z}_{an} & \underline{Z}_{bn} & \underline{Z}_{cn} & \underline{Z}_{nn} \end{bmatrix} \cdot \begin{bmatrix} \underline{I}_a \\ \underline{I}_b \\ \underline{I}_c \\ \underline{I}_n \end{bmatrix} \tag{A.34}$$

To reduce one dimension of Eq. (A.34), the neutral voltage is assumed to be equal to ground voltage. Subsequently, the effect of neutral cable is able to integrate into phase system. In order to perform integrating process, the voltage difference between phase cable and neutral cable is needed to examine. Eq. (A.35) shows the expression of the voltage difference between phase a and neutral.

$$\begin{aligned}\underline{U}_a - \underline{U}_n = \underline{Z}_{aa}\underline{I}_a + \underline{Z}_{ab}\underline{I}_b + \underline{Z}_{ac}\underline{I}_c + \underline{Z}_{an}\underline{I}_n \\ - (\underline{Z}_{an}\underline{I}_a + \underline{Z}_{bn}\underline{I}_b + \underline{Z}_{cn}\underline{I}_c + \underline{Z}_{nn}\underline{I}_n)\end{aligned} \tag{A.35}$$

After grouping by phase current, it can be obtained as

$$\begin{aligned}\underline{U}_a - \underline{U}_n = (\underline{Z}_{aa} - \underline{Z}_{an})\underline{I}_a + (\underline{Z}_{ab} - \underline{Z}_{bn})\underline{I}_b \\ + (\underline{Z}_{ac} - \underline{Z}_{cn})\underline{I}_c + (\underline{Z}_{an} - \underline{Z}_{nn})\underline{I}_n\end{aligned} \tag{A.36}$$

According to the Kirchhoff's current law, $\underline{I}_a+\underline{I}_b+\underline{I}_c=\underline{I}_n$, the voltage difference between phase a voltage and neutral can be rewritten as

$$\begin{aligned}\underline{U}_a - \underline{U}_n = (\underline{Z}_{aa} - 2\underline{Z}_{an} + \underline{Z}_{nn})\underline{I}_a + (\underline{Z}_{ab} - \underline{Z}_{bn} - \underline{Z}_{an} + \underline{Z}_{nn})\underline{I}_b \\ + (\underline{Z}_{ac} - \underline{Z}_{cn} - \underline{Z}_{an} + \underline{Z}_{nn})\underline{I}_c\end{aligned} \tag{A.37}$$

Repeating the same reduction process to phase b and c, then, the general form of impedance matrix, where the matrix dimension is 3×3, can be expressed as shown in Eq. (A.38).

$$\underline{Z}_{abc} = \begin{bmatrix} \underline{Z}_{aa} - 2\underline{Z}_{an} + \underline{Z}_{nn} & \underline{Z}_{ab} - \underline{Z}_{bn} - \underline{Z}_{an} + \underline{Z}_{nn} & \underline{Z}_{ac} - \underline{Z}_{cn} - \underline{Z}_{an} + \underline{Z}_{nn} \\ \underline{Z}_{ab} - \underline{Z}_{bn} - \underline{Z}_{an} + \underline{Z}_{nn} & \underline{Z}_{bb} - 2\underline{Z}_{bn} + \underline{Z}_{nn} & \underline{Z}_{bc} - \underline{Z}_{bn} - \underline{Z}_{cn} + \underline{Z}_{nn} \\ \underline{Z}_{ac} - \underline{Z}_{cn} - \underline{Z}_{an} + \underline{Z}_{nn} & \underline{Z}_{bc} - \underline{Z}_{bn} - \underline{Z}_{cn} + \underline{Z}_{nn} & \underline{Z}_{cc} - 2\underline{Z}_{cn} + \underline{Z}_{nn} \end{bmatrix} \tag{A.38}$$

A.2 Network Parameters of Verification Case Studies

In this section, the examined network parameters including the power generation and load conditions of each verification case study in Chapter7 are given in detail.

A.2.1 Network Parameters for Case Study1

In case study1, the existing low voltage network from DISPOWER project is utilized to evaluate both proposed hybrid load flow algorithm. All components in this case are selected from DIgSilent Power Factory program. The transformer parameter and cable parameters are listed in Table A.3 and A.4, respectively. It has to state that the cable type, which is shown in Table A.4, is utilized in all network feeders.

Table A.3: 2MVA 10/0.4kV Dyn5 transformer parameters

Parameter	Value	Unit	Description
Name	10/0.4 kV Dyn5	-	Transformer type
Sr	2	[MVA]	Rated power
Hz	50	[Hz]	Frequency
Urh	10	[kV]	Rated voltage of high side voltage
Url	0.4	[kV]	Rated voltage of low side voltage
ph	5	[x*30°]	Phase shift
uk	6	[%]	Short circuit voltage
Pcu	15.05	[kW]	Copper loss
sRh	0.5	[pu.]	Share of short circuit resistance on high side
sXh	0.5	[pu.]	Share of short circuit reactance on high side
Img	0.17501	[%]	No load circuit current
Pfe	3.5	[kW]	No load loss
uk0	6	[%]	Short circuit voltage zero sequence
ukr0	0.775	[%]	Short circuit voltage zero sequence, resistance zero sequence

Table A.4: NAYY 4x50SE three-phase four-wire cable parameters

Parameter	Value	Unit	Description
Name	NAYY 4x50SE	-	Cable type
Vr	1	[kV]	Rated voltage
Ir	0.141	[kA]	Rated current
Hz	50	[Hz]	Frequency
r	0.641	[Ω /km]	Resistance per length
x	0.084823	[Ω/km]	Reactance per length
B	0	[μS/km]	Susceptance
r0	2.564	[Ω /km]	Zero sequence resistance per length
x0	0.339292	[Ω /km]	Zero sequence reactance per length
B0	0	[μS/km]	Zero sequence susceptance per length
Rn	0.641	[Ω/km]	Neutral resistance per length
Xn	0.084823	[Ω/km]	Neutral reactance per length
Rpn	0.2564	[Ω/km]	Phase-Neutral coupling resistance per length
Xpn	0.0339292	[Ω/km]	Phase-Neutral coupling reactance per length

The various cable length of each connection is listed in Table A.5. The length is described between node connections. The node identification has already been stated in Fig.7.1.

Table A.5: Cable length of each connection

Feeder A		
From node	To node	Length [m]
BT	A1	21
A1	A2	33
A2	A3	14

Feeder C		
From node	To node	Length [m]
BT	C1	59
C1	C2	35
C1	C3	10

A3	A4	11
A3	A5	19
A5	A6	11
A5	A7	26

C1	C4	8
C4	C5	34
C5	C6	8
C5	C7	17
C4	C8	15
C8	C9	20
C4	C10	11

Feeder B		
From node	To node	Length [m]
BT	B1	45
B1	B2	7
B2	B3	16
B1	B4	18
B4	B5	22
B4	B6	23

Feeder D		
From node	To node	Length [m]
BT	D1	58
D1	D2	17
D1	D3	43
D1	D4	16
D3	D5	16
D3	D6	15

The applied asymmetrical load and applied asymmetrical generator on each node is portrayed in Table A.4. The applied generator is considered as a negative load, which is recognized with minus sign. All three-phase applied power is assumed to be a constant power star connected spot node. The applied reactive power is calculated with the 10% of the active power.

Table A.6: Applied load and generation power

	Load Feeder A		
Node	P_a [kW]	P_b [kW]	P_c [kW]
A1	2.00	2.00	2.00
A2	1.00	1.00	0.40
A3	0.00	0.00	0.00
A4	9.00	9.00	15.0
A5	0.00	0.00	0.00
A6	9.00	9.00	9.00
A7	8.00	6.00	6.00

	Load Feeder C		
Node	P_a [kW]	P_b [kW]	P_c [kW]
C1	0.00	0.00	0.00
C2	2.00	2.00	2.00
C3	-5.00	-5.00	-5.00
C4	0.00	0.00	0.00
C5	0.00	0.00	0.00
C6	5.00	4.00	5.00
C7	30.0	30.0	30.0
C8	-10.0	-15.0	-10.0
C9	12.0	12.0	16.0
C10	8.00	5.00	5.00

	Load Feeder B		
Node	P_a [kW]	P_b [kW]	P_c [kW]
B1	0.00	0.00	0.00
B2	2.00	1.00	3.00
B3	-5.00	-5.00	-5.00
B4	0.00	0.00	0.00
B5	25.0	30.0	25.0
B6	4.00	4.00	4.00

	Load Feeder D		
Node	P_a [kW]	P_b [kW]	P_c [kW]
D1	0.00	0.00	0.00
D2	7.00	4.00	7.00
D3	0.00	0.00	0.00
D4	7.00	7.00	7.00
D5	-10.0	-10.0	-10.0
D6	6.00	8.00	6.00

A.2.2 Network Parameters for Case Study2

To verify and observe the operation of proposed compensation technique in sequence hybrid analysis method, the strong unbalanced IEEE 123 nodes test feeder is subsequently considered. The test feeder operates at a nominal voltage of 4.16 kV. While this is not a popular voltage level it does provide voltage drop problems, hence, the Voltage/VAR Control trough reactive power injection [152] is taken into account to handle this problem. The modified injected reactive power profile is stated in Table A.7.

Table A.7: Reactive power injection profile [152]

Node	Q_a [kvar]	Q_b [kvar]	Q_c [kvar]
149	725.00	475.00	575.00
3	0.00	0.00	1.20
8	1.90	1.41	1.72
14	2.22	0.00	0.00
17	0.00	0.00	1.91
21	2.42	1.70	2.04
24	0.00	0.00	1.97
27	1.98	0.00	2.11
30	2.22	1.81	2.02
32	0.00	0.00	2.14
38	0.00	2.11	0.00
42	2.67	2.45	2.14
47	2.56	2.34	2.45
51	2.67	2.45	2.80
57	2.87	2.77	2.94
63	3.01	2.98	2.98

Node	Q_a [kvar]	Q_b [kvar]	Q_c [kvar]
69	3.15	0.00	0.00
75	0.00	0.00	3.11
76	3.45	3.14	3.56
80	3.56	3.34	3.55
81	3.45	3.67	3.68
86	0.00	3.84	0.00
89	3.69	3.84	3.77
93	3.78	3.90	3.97
97	4.01	3.92	4.13
100	4.11	3.99	4.15
101	4.44	4.01	4.24
106	0.00	4.21	0.00
110	4.67	0.00	0.00
113	4.63	0.00	0.00
300	4.45	4.68	4.56

Another modified element is a substation. The substation model is replaced by the 5MW Dyn5 transformer model, whose parameters are listed in Table A.8. The rest of test feeder configurations are kept as the providing data in [153].

Table A.8: Modified substation model

Parameter	**Value**	**Unit**	**Description**
Name	115/4.16 kV Dyn5	-	Transformer type
Sr	5	[MVA]	Rated power
Hz	50	[Hz]	Frequency
Urh	230	[kV]	Rated voltage of high side voltage
Url	4.8	[kV]	Rated voltage of low side voltage
ph	5	[x*30°]	Phase shift
uk	2	[%]	Short circuit voltage
Pcu	1.7	[kW]	Copper loss

sRh	0.5	[pu.]	Share of short circuit resistance on high side
sXh	0.5	[pu.]	Share of short circuit reactance on high side
Img	0.24	[%]	No load circuit current
Pfe	1.5	[kW]	No load loss
uk0	2	[%]	Short circuit voltage zero sequence
ukr0	1.02	[%]	Short circuit voltage zero sequence, resistance zero sequence

A.2.3 Network Parameters for Case Study 3

To demonstrate the application of hybrid load flow calculation for the interconnected clusters system analysis, the IEEE 37 nodes test feeder is considered. To represent the behaviors of interconnected clusters network, the test feeder is modified through the three general cluster levels: superordinate, ordinate and subordinate cluster level. Moreover, there are two other modified elements, as listed in the following:

- The regulator between line segments 799-701 is removed
- The substation model is replaced with Dyn5 transformer model, whose parameters are listed in Table A.9

Table A.9: Modified substation model

Parameter	Value	Unit	Description
Name	230/4.8 kV Dyn5	-	Transformer type
Sr	2.5	[MVA]	Rated power
Hz	50	[Hz]	Frequency
Urh	230	[kV]	Rated voltage of high side voltage
Url	4.8	[kV]	Rated voltage of low side voltage
ph	5	[x*30°]	Phase shift
uk	2	[%]	Short circuit voltage
Pcu	1.7	[kW]	Copper loss
sRh	0.5	[pu.]	Share of short circuit resistance on high side
sXh	0.5	[pu.]	Share of short circuit reactance on high side
Img	0.24	[%]	No load circuit current
Pfe	1.5	[kW]	No load loss
uk0	2	[%]	Short circuit voltage zero sequence
ukr0	1.02	[%]	Short circuit voltage zero sequence, resistance zero sequence

All line configurations and load profile in test feeder are kept as the providing data in [153].